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THE INFLUENCE OF GEOGRAPHIC CONDITIONS UPON ANCIENT MEDITERRANEAN STOCK-RAISING*

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CONTENTS

Geographic Deterrents to Pastoral Nomadism.—" It is weather rather than soil that determines the harvest " in Mediterranean lands, said the Greek Theophrastus. It was climate which determined the pasturage there, causing its mediocre quality, its limited quantity and its seasonal distribution through the year. The poor endowment of this region with good grazing revolutionized the economic life of all those pastoral tribes who pushed into the Mediterranean Basin, from the well-watered Danube valley on the north and the vast undulating grasslands on the east. Here Nature offered for their occupancy only limited areas, whose boundaries were drawn by the " unpastured seas," to use Homer's expression. Here steep mountain barriers discouraged nomadizing, while the low valleys and narrow coastal plains provided fodder only half the year. Therefore from the arrival of the Israelites and other Semitic hordes in Palestine to that of the shadowy Pelasgians in Greece and Italy, these conditions forced a more or less rapid decrease in the flocks and herds of the pastoral invaders, and hastened the

* Presidential address before the Association of American Geographers, Washington Meeting, Washington, 1921.

advance from nomadism to sedentary agriculture. The Jewish Scriptures, the Iliad and Odyssey, the traditions, customs and religious institutions of primitive Latins, Celts and Iberians, all point to a former preponderance of stock-raising gradually superseded by tillage. Grazing survived, but hardly as an adjunct of tillage. It evolved along lines alien to the rainy lands of the north and to the semi-arid lands to the east. It developed the semi-nomadic summer shift to the highland pastures, familiar in the Swiss Alps and the Scandinavian mountains, but arising from quite different geographic causes, and attended by quite different economic results.

Stock-raising in the ancient Mediterranean world bore the unmistakable impress of its environment. It was conditioned primarily by the summer drought. This destroyed pasturage in the lowlands for two to six months, according to the latitude, and permitted the shallow-rooted herbage to survive only on swampy coastal belts, deltaic flats and mountain-locked lake basins in which the ground-water table was high. Such choice but limited spots furnished the wet meadows or marsh pastures, which the ancients reserved for their brood mares, horses and fine cattle, and which they sometimes guaranteed against failure in exceptionally dry seasons by artificial irrigation. Yet even these grassy areas shrank to mere patches of green as the summer advanced, unless the streams which watered them flowed down from high mountains with lingering hoods of snow.

Effect of Relief Upon Mediterranean Pasturage.—The Mediterranean lands made some compensation for the summer drought by their prevailing mountain relief, which provided summer pastures on the heights. The great altitude of the young folded ranges and massive horsts which almost surround the Mediterranean and its Black Sea alcove, their extensive distribution from the Rif Atlas to the densely wooded Caucasus, and their immediate proximity to the vapor-yielding seas, all combined to sprinkle the Mediterranean lands with lofty climatic islands of persistent verdure, wherever the slopes rose high enough to take a toll of moisture from the passing clouds. Here the lowly herbage of the sod flourished the summer through, screened from the sun by the deciduous forests of the upper slopes, nourished by the bed of moist humus about their roots. The summer pastures of the Mediterranean highlands, however, did not offer the variety of grasses and nutritious herbs found in the Alpine meadows farther north; nor did they wear so long the covering of snow which subjects the soil to a slow process of saturation and promotes growth through the ensuing months of sunny days. Therefore, except on the high Alpine rim of the Mediterranean Basin, the flocks and herds grazing

on the mountain pastures have always had to eke out their grass diet by the fresh shoots and accessible twigs of the deciduous trees. This supplementary fodder was undoubtedly more abundant and varied in ancient times than now, when the forests are the thin and deteriorated residue left by centuries of denudation. Moreover, the original forest covering conserved the moisture in the soil of the slopes, and thereby maintained a richer pasturage of herbs and grasses than exists there today.

The quality of the mountain pastures declined from north to south and from west to east within the long flattened ellipse of the Mediterranean lands, and it fell off rapidly from the more rainy western flank of mountainous coastland or peninsula to the rain-shadow on the eastern side; for in these directions the summer drought increased in length and intensity. The northern mountains, whose rainfall approximated the all-year precipitation of middle Europe, had good and reliable summer pastures which supported herds of horses, cattle and mast-fed pigs, besides flocks of sheep and goats. The southern mountains, located below the 40th or 41st parallel, were covered up to 2,000 or 3,300 feet (600 to 1,000 meters) with the typical thorny and leathery Mediterranean vegetation, varied by occasional groups of deciduous trees growing in deeper pockets of soil, where humus and moisture collected. These lower slopes furnished pasturage fit only for sheep and goats, except in spring and the warm rainy autumn when the short-lived grasses lifted their green stalks.

Above this limit the less fastidious flocks found ampler and better pasturage. Cattle and horses, however, which needed succulent herbage, found suitable grazing only in high level valleys or lake basins which combined deep soil with summer showers, like the lake-strewn highlands of ancient Arcadia and Epirus or the longitudinal valleys of the Apennines. In the more arid southern zone, the best summer pastures were located on westward-facing ranges, like the western Apennines, the mountains of Elis, and the high valleys of "many-fountained" Ida, whose cattle pastures in Homeric days reflected the location of this Mysian mountain between rain-bearing winds from the Aegean Sea and those from the Propontis or Marmora. Mountains or limestone plateaus which barely attained the critical elevation of 3,300 feet (1,000 meters), like the Judean Plateau or the Barca Plateau of northern Africa, yielded ephemeral grasses even on their summits. These countries, therefore, had to restrict the raising of horses and cattle to the scant water-soaked or irrigable lowlands at their base, or draw on the stock of the pastoral nomads along their steppe borders. Only sheep and goats, led about by some boy shepherd of the hills, could thrive on these uncertain upland pastures.

Relation of Stock-raising to Sedentary Agriculture.—Conditions of climate and relief in Mediterranean lands greatly restricted stock-raising as an adjunct of sedentary agriculture. In fact, the two industries were pretty effectually divorced. The flocks and herds fed in winter on the untilled lands, the lowland meadows, and stubble fields of the home farm; but before the advent of summer they were driven out for their half-year on the highland pastures. This is the rule also today. The author has seen sheep feeding on the crest of the Cithaeron range (elevation 2,800 feet or 850 meters) between Attica and Boeotia in early April, while 100 miles farther north the flocks were still grazing on the lake plain of Thessaly, because the middle and upper slopes of the Olympus massif were covered with snow. This divorce of stock-raising from tillage had a marked influence upon the latter. For six months the manure of the flocks and herds was lost to the home fields. To replace it the ancient Mediterranean farmer had to exercise a Chinese-like economy in devising various other fertilizers, even to the ploughing-in of green crops as early as 400 B. C.;[1] but he probably never compensated the soil for the moisture-conserving qualities of the animal manures.

Owing to the lack of home pastures, moreover, the animals kept on the farm were restricted to the imperative needs of agricultural labor, and were stall-fed throughout the year. Their feeding, moreover, called for the utmost economy. The arable land, scant at best because of the predominant mountainous relief, was carefully apportioned to field crops, gardens, fruit orchards, olive plantations and vineyards, according to its suitability for each. Meadows for hay or forage crops could be maintained through the summer only by irrigation; but irrigable fields were scarce and valuable. Natural meadows were confined to wet lands too low to be drained,[2] and were usually of small extent. Fodder crops of great excellence were raised, but forage was doled out to the work animal with a skimping hand. The ancient farmers cultivated various fodder legumes by irrigation during the dry season, reaped several harvests therefrom where the water sufficed, and let the fields serve for green forage during the winter.[3] They relied chiefly on alfalfa or Medic clover (*Medicago sativa*), which was introduced into Greece by the invading Persians in 490 B. C. It yielded four to six crops a year and lasted ten years from one sowing.

[1] Xenophon, *Oeconomicus*, XVII, 10.

[2] Theophrastus, *Historia Plantarum*, Bk. IV, ch. VIII, 13. Aristotle *De Animalibus*, VII, ch. 23, 6. Naumann and Partsch, *Physicalische Geographie Griechenlands*, p. 404. Breslau, 1885.

[3] Pliny, *Historia Naturalis*, Bk. XVIII, ch. 30–43. Columella, Bk. II, 7 and 10; Bk. V, 12.

To free it from weeds, it was cut close to the ground each spring. The weeds thereby perished, but the alfalfa survived, owing to its deep root system.[4]

Barley and spelt, an inferior wheat, were the feed grains for stock throughout the Mediterranean basin. Rye and oats, which required a moist climate, were for a long time scarcely known. Oats were regarded as a harmful weed in Virgil's time,[5] but a few decades later Columella mentions them as a fodder crop.[6] Rye was raised only in the moister northern parts of the Mediterranean region. Thracians and Macedonians planted it in the 2nd century,[7] and probably earlier, in the 4th century B. C., if Theophrastus is correct. The ancient Taurini, who occupied the upper Po valley about Turin and whose name indicates a cattle-raising folk, raised rye in their well-watered territory.[8] Pliny mentions rye in a mixed fodder crop of rye, spelt and beans,[9] a combination which shows how far the Roman farmers had advanced in the art of feeding cattle, after the enormous grain importations into Italy caused field agriculture to be superseded by stock-raising.

Kind, Number and Distribution of the Animals Raised.—The character of Mediterranean pasturage determined the kind, number and distribution of the animals raised. Pigs were associated with the rainier districts of the north and west, where mast-yielding forests abounded; they were eliminated by climatic conditions from Palestine, Syria, and the semi-arid interior of Asia Minor. In all these regions the climatic inhibition was echoed in a religious taboo. Sheep and goats represented the survival of the fittest for Mediterranean pasturage, and therefore began their successful competition with other kinds of stock at an extraordinarily early date. On the dry fields of Palestine they alone could nibble a living from the poor, thin herbage. Though exempt from farm labor, they furnished milk, cheese, leather, wool and hair for textiles. When slaughtered for meat, their small size was an advantage in iceless homes and in a region where the winter cold rarely sufficed to freeze meat.

Cattle and horses, on the other hand, which required good feeding, were associated even in the time of Homer and Solomon with advanced

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[4] Aristotle, History of Animals, III, 21; VIII, 8. Strabo, XI, ch. XIII, 1, 7. Pliny, Bk. XVIII, ch. 16.

[5] Vergil, Georgic, I, 77. Pliny, Bk. XVIII, 149.

[6] Columella, II, 19, 32.

[7] Galen, VI, 514.

[8] Pliny, Bk. XVIII, ch. 16, 40.

[9] Varro, I, 31, 5. Columella, II, 7, 2. Pliny XVIII, ch. 16, 41.

sedentary agriculture, the possession of marsh meadows, and the maintenance of fodder crops through the dry season by means of irrigation. Their presence reflected quite accurately the geographic possibilities of good or fair summer pasturage. They were therefore rare in Palestine but relatively abundant in Italy, whose long narrow peninsular form, high relief and more northern location curtailed the dry season and insured occasional summer showers, while its extensive plains of moist or swampy alluvium provided conditions for wet pastures in the Po, Arno and Adige valleys and certain coastal lowlands. These conditions also permitted Italy to abandon field agriculture, as opposed to horticulture and viticulture, and to resort to stock raising on a large scale, when Rome's over-rapid territorial expansion and the enormous importation of foreign grain had ruined the small peasant.

Meat Diet in Mediterranean Lands.—The pasturage conditions were further reflected in the amount and kinds of meat used as food in the ancient Mediterranean world. While the flood-plain of the Nile supported cattle, sheep, goats and pigs in relative abundance and supplied meat to the tables of the well-to-do, everywhere else the meat diet was restricted, just as it is today. In Palestine and Greece, a religious festival attended by the sacrifice of a ram, lamb or kid was the chief occasion for the appearance of meat on the table of the common people. These conditions held in Palestine from the earliest times and emphasized the importance of olive oil as a substitute, as revealed all through the Scriptures. The consumption of beef decreased from north to south and from west to east. Except in Italy, it declined also from the earlier to the later epochs with the deterioration of the mountain pastures and the growing pressure of population upon the irrigable lands of the plains. The sustaining food of beef and swine meat which characterized Homeric Greece was greatly attenuated by the 7th Century B. C., and by the 5th century came rarely on the daily table. A goat or a pig was the treat for a festival in Athens, and beef was enjoyed by the common man only at public banquets on the occasion of public sacrifices.[10] Lucky people like the Thessalians and Boeotians, who had good pastures and fat kine in their old lake basins, were scorned as gluttons but were none the less envied. If Solon forbade the sacrifice of an ox for a funeral feast as a sumptuary law in the interest of economy,[11] this prohibition may reflect the increasing price of cattle in Attica, a land poor in pastures.

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[10] E. Speck, *Handelsgeschichte des Altertums*, vol. II, pp. 537-8. Leipzig. 1901, W. S. Davis, *A Day in Old Athens* p. 180. Boston, 1914.

[11] Plutarch, Solon, XXI.

Meat was a luxury for feast days also in the early Republic of Rome; but with the rapid acquisition of more ample and nutritious pastures, as the northern Apennines and the Po valley were conquered and annexed, and with the transition to large-scale stock farming following the second and third Punic wars, beef became a more common article of food; lamb, mutton and goat's meat were cheap, and every form of *porcina* or hog meat was in general demand.[12] Meat figured conspicuously as food among the large patrician and official classes of the capital, where wealth was centralized, and therefore doubtless occasioned the sharp advance in the market price of all cattle which made the older Cato rank stock-raising as the most remunerative branch of tillage;[13] but among the growing proletariat and the vast number of slaves, salt-fish, supplemented by the poorer grades of olives and olive oil, probably took the place of meat, as it did among the common people of Greece.[14] In the early centuries of the Roman Republic, when a balanced system of agriculture prevailed, and at all times elsewhere in the Mediterranean world an immense impulse was given to the ancient fisheries by the need to supply the place of meat. The wide sea ventures of the ancient tunny fleets, therefore, may be regarded as the joint effect of ample coastlines and meager pastures. And when the early Christian church imposed meatless days or fasts upon the Greek and Roman adherents within the Empire, the restriction worked little hardship to the mass of the people, whose dietary stand-by was salt fish. This reflection leaves us with the query how far climatic conditions may discount the merit acquired by certain religious observances.

The scrupulous economy of the grazing and meadow lands in the ancient Mediterranean world reveals itself in various secondary or derivative effects of geographic conditions. Cows and oxen were raised at a minimum cost on the out-pastures of the mountains and marshes, and brought to the home farm when old enough to work. There they were employed for agricultural labor in preference to the horse, which had fewer economic uses and yet required the best feed. We read of ox-wagons and horse-carts in Athens, used to transport building materials to the Acropolis in the time of Pericles,[15] but mules and oxen were more generally employed as draft animals.[16] The unassuming ass was the pack-animal for the rough mountain paths and ill-made

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[12] H. Blümner, *Die Römischen Privataltertümer*, pp. 174–175. Munich, 1911.

[13] Cicero, *De Officiis*, II, 25.

[14] E. Speck, *Handelsgeschichte des Altertums*, vol. II, p. 477. Leipzig, 1901. Boeckh, *Staatshaushaltung der Athener*, Vol. I, pp. 127-130. Berlin, 1886.

[15] Plutarch, Pericles, XII.

[16] A. E. Zimmern, The Greek Commonwealth, p. 270. Oxford, 1911.

tracks which prevailed in the Mediterranean world before the expansion of the imperial road-builders of Rome.

THE HORSE IN MEDITERRANEAN LIFE.—In most Mediterranean lands, horses appear as luxury articles from very early times. Only in the northern and rainy parts of the region, where good pastures were found, did horses become a commonplace. Owing to the cost of raising and maintaining them, they were the luxury of the rich, the special privilege of nobility and royalty, whether among the Jewish kings and princes of ancient Palestine,[17] or the Greek and Trojan chieftains warring on the plains of Ilium;[18] whether among the landed aristocracy of the *Hippobotae* or "horse feeders" of Greek Euboea, or the wealthy class of *Hippes* who constituted the small equestrian order of Athens in the 7th and 6th centuries B. C.,[19] or the *nouveau riche* of Rome who formed the order of the *equites* or knights, among whom the gold ring, the purple-bordered toga and the prancing steed, were the badge of all their tribe. The Eupatrid family of the Alcmaeonides of Athens, like other noble clans of the commonwealth, acquired riches, raised horses on their landed estates, won prizes in the four-horse chariot races in the Olympic Games, and thus arrived at distinction.[20] Vergil specifies the raising of fine sleek-coated horses as the congenial occupation and conspicuous characteristic of the Trojan and Roman nobles.[21] When the poet describes the equestrian evolutions of the Trojan lads at the *Ludus Trojae* or funeral games of Anchises in Sicily, he makes it clear that only the little aristocrats of Aeneas' exile band participated in this miniature cavalry display.[22] Does some such fact as this explain the patrician beauty and noble bearing of the mounted boys in the frieze of the Parthenon? No beggar ever got on horseback in the Mediterranean region: that edifying spectacle was reserved for rainier lands.

Cavalry and chariot service in war became the obligation of the rich, and made horses the concomitant of war throughout the Mediterranean.[23] Aside from their appearance in religious processions, sacred games and races, war was their essential use. The amount of cavalry which each country could command depended upon the supply of wet meadows and therefore often fluctuated with the expansion and

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17 II Samuel, XV, 1. I Kings, I, 5. Jeremiah, XVII, 25.

18 J. D. Seymour, Life in the Homeric Age, p. 349. N. Y. 1907.

19 Herodotus, V, 77. Plutarch, Pericles, XXIII. Aristotle, Politics, VI, 7.

20 Herodotus, VI, 125. E. Curtius, History of Greece, vol. I, p. 369. N. Y. 1867.

21 Vergil, Aeneid, VI, 653–655.

22 Ibid. V, 558–570.

23 Ibid. I, 444; VI, 653–655. Proverbs, XXI, 3.

contraction of the national frontiers, as the boundaries included or excluded such natural pastures. The few states with abundant and superior pastures became famous for their cavalry and were sought as allies in war; from them horses were purchased or mounted troops were hired by commercial states of large revenue like Athens, which in the days of its wealth could import horse feed. Horses, like cattle, were scarce in Athens, where climate, relief and the composition of the soil were all adverse to good pasturage. Therefore the Athenian cavalry was always small, only 100 to 300 horsemen originally,—a negligible force at the Battle of Marathon,—and never numbering more than a thousand, who were occasionally reinforced by mounted Scythian bowmen.[24] Hence the Athenian state, in the protracted wars with its rivals, always sought the alliance of the few Greek commonwealths which had a numerous cavalry.

The prevailing rugged relief of the Mediterranean lands tended to restrict the employment of cavalry and chariots in war, and in some districts quite inhibited their use. It dictated the choice of broad and level battlegrounds by generals with strong mounted forces, who therefore manoeuvred for place. Thus the northern Syrians and Philistines, who had numerous chariots, drew the horseless Israelites into battle in the lake-plain of Merom and the plain of Esdraelon.[25] The Persian invaders of Greece in 490 B. C. selected the plain of Marathon for their decisive battle, by the advice of the traitor Hippias, and later the plain of Platea, because the defending forces were weak in cavalry and the Persians were strong.[26] Attica was not a country whose terrain permitted the free operation of mounted troops, but Boeotia was;[27] hence the significance of the battle fields of Chaeronea and Coronea, located in lake and valley plains of Boeotia, for the Macedonian conquest of Greece. Hannibal, on his invasion of Italy, could employ his Numidian cavalry to an advantage in the broad Po lowlands at Ticinus and Trebia, the lake plain of Trasimenus and the coastal plain of Apulia at Cannae. When caught by the Romans in a mountain valley where his cavalry was useless, he escaped from the trap by strategy.

Economy of Pastures and Improvement of Animal Breeds.—The paucity of the Mediterranean pastures necessitated their intelligent and economic use. This requirement led to the improvement of the animal breeds by artificial selection at an early period, in Egypt

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24 A. Boeckh, *Die Staatshaushaltung der Athener*, vol. I, pp. 330-333. Berlin, 1866.

25 Joshua, XI, 4, 5. 1 Samuel, XIII, 5. Judges, IV, 3; V. 19–22.

26 Herodotus, VI, 102.

27 Herodotus, IX, 13.

even under the old Empire in 3,000-2,500 B. C.[28] It was well established in Greece in the time of Aristotle or earlier; it developed into a broadly applied system in Italy and Sicily, and appeared in Cyrene, Africa and Spain. The process was fostered by the early live-stock trade, due to the uneven distribution of pasturage, which sprang up between districts of good and poor grazing. Surplus animals from all the pastoral hinterlands reached the Mediterranean markets where they were exchanged for grain or manufactured commodities. Occasionally they came as tribute; and since the kind and breed of animals were generally specified by the law imposing the tributes, such animals were probably the best of their kind. This was particularly true in the case of horses. Overseas trade in live-stock was facilitated by the early development of horse transports as a branch of the merchant marines of both Phoenicia and Greece. Aside from the imperative need of transporting cavalry for war, which was well established by 490 B. C.,[29] the risk and expense of taking animals on long voyages in small boats must have been prohibitive except for choice specimens which would command high prices; and these would naturally be used for breeding purposes. We hear of Venetian horses in Sparta in the middle of the 7th century B. C.[30] Fine horses and mules of racing stock were brought from African Cyrene and various cities of Sicily as early as 494 B. C. to compete in the sacred games of Greece at Corinth, Delphi and Olympia.[31] It is easy to imagine that the sacred precincts of the games became the scene of busy horse trading after the prizes had been awarded, and that thus various strains were mixed and eventually improved.

The evidence points to a very early importation of the superior Thracian horses into Italy. Vergil would hardly have dared to make Aeneas find Thracian horses the property of the local kings in Sicily and Latium,[32] if the anachronism had been all too violent. The fact that the Carthaginians employed horse transports in 488 B. C. in a military expedition to Sicily[33] suggests that they may have earlier imported choice animals from Phoenicia to stock their big landed estates in Africa, as is indicated in the Aeneid when Dido presents the boy Ascanius with a fine Sidonian steed.[34] The nature of the horse as a luxury article and its highly specialized use for chariot

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[28] Erman, Life in Ancient Egypt, pp. 436-438. London, 1894.

[29] Herodotus, VI, 95; VII, 87, 97.

[30] E. Speck, *Handelsgeschichte des Altertums,* vol. II, p. 483. Leipzig, 1901.

[31] Pindar, Odes, Pyth. I, II, III, VI; Olym. I-III, VI; Nem. IX.

[32] Vergil, Aen. V, 565–567.

[33] Diodorus Siculus, Bk. XI, chap. II.

[34] Vergil, Aen. V, 571.

races and war, requiring speed and endurance, doubtless contributed to the early improvement of the equine strains through artificial selection, and therefore to a peculiarly discriminating trade in the animal. The horse breeds were improved also by superior feeding, by the reservation of the best green pastures for the mares and colts, and by the maintenance of stud-farms at great distances, wherever natural pastures afforded green fodder all year round. This was noticeable among Macedonian, Greek, Sicilian, and Roman nobles and plutocrats.

Regions of export for selected breeds of horses and cattle were characterized by marsh-meadows, heavy rainfall with summer showers, or by the moist soils of lacustrine basins surrounded by high mountains. Such regions were Egypt and the Cilician lowland; Thrace, Thessaly, Messinia, Arcadia, Elis, Argos and Epirus in Greece; Apulia, the Po valley, and Venetia in Italy, together with Sicily. In the Iberian peninsula only the Guadalquiver lowlands or Baetica had attained a sufficiently advanced economic development to yield superior breeds.

The best sheep and goats were sought for breeding purposes in regions of dry pasturage near old industrial centers famous for their textiles, like Miletus, Megara, Athens, Tarentum, Corduba and Gades. These districts had selected their breeds for the fineness, length and color of their wool or hair; and further to improve the quality of the fleece, they covered the sheep with skins.[35] Diogenes said that the children of the Megarans ran about naked, while their sheep were clothed. This trade in improved strains began very early. We read, for instance, that Polycrates of Samos (532 B. C.) imported goats from the islands of Naxos and Scyros, sheep from Attica and Miletus, and swine from Sicily.[36] The demand for wool and goat's hair for textiles was imperative. Cotton was as yet unknown to the Mediterranean farmers, and the cultivation of flax for fibre was practically restricted to Egypt for centuries, for there chiefly was found the rich, moist alluvial soil which it required. Such soil was found in other Mediterranean lands in limited quantities, and seldom could it be spared from the more important wheat, especially since both Hebrew, Greek, and Roman farmers knew that flax exhausted the ground.[37] Therefore flax culture came late into Italy and then was centered in the alluvial plains of the Po valley.[38] Linen was sparingly used for

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[35] H. Blümner, *Gewerbe und Kunst bei Griechen und Römern*, vol. I, pp. 91–98, Leipzig, 1875.

[36] Athenaeus, XII, 57.

[37] H. Vogelstein, *Landwirthschaft in Palästina zur der Mischmah.* Berlin, 1894. Columella, II, 10, 17. Theophrastus, *De Causis Plantarum, IV*, 5, 4.

[38] Pliny, XIX, 9.

clothing even in the first century of the Empire, when it was a luxury article for the Caesars and the rich.[39] In contrast, every rocky island unfit for tillage supported flocks of goats, while goats and sheep flecked every mountain side in summer, and drifted over every plain and hill in winter.

Let us now examine the various Mediterranean countries in the light of these general principles, and get the picture of stock-raising in each from the data which have come down to us.

Stock-raising in Egypt.—Ancient Egypt had cattle and horses in abundance both for home use and export. In time of famine they were exchanged for the government grain under Joseph's rule.[40] To the Greeks the Nile was "the stream where graze the goodly kine."[41] Compare the vision of Pharaoh before the seven year's famine: "There came out of the River seven well-favored kine and fat-fleshed, and they fed in a meadow."[42] The inundations of the Nile irrigated an area large enough both for plough land and pasture. Moreover, the marshes of the Delta, which remained unreclaimed long after the river valley proper had been brought under cultivation and which were in part unreclaimable, furnished natural pastures when the fodder supply in the farm land ran low, prior to the summer flood. Thither the cattle were driven from the south every year, and were entrusted to the local marsh-men. These were an uncouth people but professional herdsmen; they still persisted as such in the time of Marcus Aurelius (180 A. D.), when the Romans called the marshes of the Delta the *bucolia* or cattle pastures.[43] The Nile valley furnished various irrigated forage crops, which fed the home cattle and horses penned up in the mound villages during the summer floods.[44] Under these favorable geographic conditions, Egypt from 3000 B. C. maintained a careful system of cattle-breeding, which resulted in several varieties of ordinary and humped cattle;[45] and it supported the horse-breeding industry which supplied an export trade to Palestine, Syria and the Hittite country of Asia Minor.

The Egyptian horses were carefully bred and were evidently superior to the native stock of south-western Asia, because they commanded

[39] H. Blümner, *Die Römischen Privataltertümer*, p. 241. Munich, 1911.

[40] Herodotus, II, 37; Genesis, XLVII, 15-18.

[41] Aeschylus, The Suppliants, 834.

[42] Genesis, XLI, 2.

[43] A. Erman, Life in Ancient Egypt, pp. 439-444. London, 1894; Mommsen, Provinces of the Roman Empire, Vol. II, p. 284. New York, 1887.

[44] Diodorus Siculus, Bk. I, ch. III, 36.

[45] A. Erman, Life in Ancient Egypt, pp. 436-437. London, 1894.

high prices in export. The large number of chariots and cavalry in the Egyptian Armies from the 14th century, B. C. indicates horse-raising on a big scale. This was rendered possible by the ample grain and fodder crops of the Nile valley, and in turn it rendered possible the broad artificial selection which improved the breed. The original equine stock came in with the Hyskos invaders (1700 B. C.), but it was probably improved by crossing with the fine horses of the Libyan tribes, who began pushing into the western margin of the Delta from the 13th century. These nomads, like the later Bedouins, apparently developed an animal distinguished by speed and endurance, in response to the requirements of thinly scattered pasturage, desert warfare and border raids. The excellence of this Libyan breed reappeared in the race horses of Cyrene, which frequently carried off the prizes in the Olympic Games.[46]

Stock-raising in Palestine.—Palestine, because of its climate, geology, relief and the deep Jordan rift which makes the highland overdrained, has always had scant natural grazing for cattle and horses, though sheep and goats can find enough forage of a poor kind. But flocks and herds alike suffered from the frequent droughts or half-droughts which visited the land, when cow and ewe, like the hart, "panted for the water-brooks." The ancient breed of sheep was undoubtedly the broad-tailed variety, which probably came from arid Asia by way of Arabia.[47] It was fortified against a season of poor pasturage by the store of fat in the immense tail, translated "rump" in the Bible but now given as "fat tail" in the revised version.[48] The limestone plateau of Judea and the lower Negeb to the south were covered with herbage after the March rains, and furnished a nutritious but transitory pasturage. Here in the spring grazed "the cattle upon a thousand hills" of which the psalmist sang[49] with more religious fervor than scientific accuracy. By midsummer all was parched and brown. Earlier still faded the belt of green to the east and south, the short-lived "pastures of the wilderness."[50] The flood plain of the lower Jordan, which the sheik Lot selected for his portion of Palestine because it was well-watered, was indeed saturated with moisture after the melting of the snows on high Hermon (8,700 feet or 2,653 meters)

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[46] O. Keller, *Die Antike Tierwelt*, Vol. I, pp. 219-221, 1909. W. Ridgeway, Origin and Influence of the Thoroughbred Horse, pp. 216-223. Cambridge, 1905.

[47] Herodotus, III, 113.

[48] Exodus, XXIX, 22; Leviticus, III, 9.

[49] Psalms, I, 10.

[50] Joel, I, 18–20.

to the north; but its grass soon perished in the furnace heat of the deep rift (1,293 feet or 394 meters below sea-level).

Only on the narrow coastal plain of Sharon and the valley floor of Esdraelon did the grass never wholly fail in summer. These therefore were the chief natural pastures for the cattle of King David.[51] Both districts are fed by springs from the porous limestone plateau and have a high water-table which ensures a modicum of moisture to their soil. Sharon extends 50 miles from Joppa to Carmel, with a varying width of 6 to 12 miles. Swamps half a mile wide border its streams, whose outlets are obstructed by the coastal dunes, and many small lagoons are strung along its shore. Sharon is today a district of pastures and scattered farms, between which stretch belts of evergreen oak, the remnant of the forest described by Strabo and Josephus.[52] Much of it was under cultivation in ancient times, but the remainder yielded the best pasturage of Palestine and nourished superior cattle, which are praised in the Talmud.[53] The old lacustrine plain of Esdraelon, surrounded by Mount Carmel and the hills of Samaria and Galilee, located farther north than Sharon and better watered, is a natural meadow land. Its broad, level floor lies so little above sea-level and has such a slight drainage slope that much of it is marshy during winter and spring, so that the modern road crosses it on a dyke. This is the plain where Sisera and his 900 war chariots got mired during a battle when the Lord sent a sudden storm to assist the Israelites.[54] The value of these wet meadows was recognized in ancient Palestine. "Blessed are ye that sow beside all waters, that lead out thither your ox and your ass." The Bible gives a picture of poor and uncertain grazing for the larger animals elsewhere west of Jordan. Allusions to "fat pastures" and "large pastures" occur only when the prophets, in rare moments of optimism, indulge in hyperbole to describe the material blessings promised to a repentant Israel[55] by an irascible deity, whose moods varied with the weather, not as an effect but as a cause.

East of Jordan, the plateau belt of Gilead, Golan and Bashan rises 2,600 to 4,400 feet (800 to 1,300 meters) above the sea, and receives from 16 to 24 inches (400 to 600 mm.) of rainfall in Golan, but less in Gilead to the south.[56] This sufficed in ancient times, as

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[51] I Chronicles, XXVII, 29.

[52] General Staff Map, No. 2321, Jaffa Sheet. E. Banse, *Die Turkei*, p. 371, Braunschweig, 1919.

[53] Hastings, Dict. of the Bible, article Sharon. Isaiah, XXXV, 2; LXV, 10.

[54] Judges, IV, 3, 13; V. 19–22.

[55] Ezekiel, XXXIV, 14. Isaiah, XXX, 23.

[56] E. Banse, *Die Turkei*, pp. 361-362. Braunschweig, 1916.

today, for good or even excellent grasslands,[57] over which cattle wandered in a half-wild state in charge of nomadic herdsmen. Such were the "bulls of Bashan" and the herds whose yield figured in the tribute paid to the kings of Israel and Judea, and in the produce sent to the western markets. This district furnished booty in the form of cattle to the Israelite conquerors;[58] and it was appropriated by the tribes of Gad who were essentially herdsmen.[59]

The small natural meadows of ancient Palestine seem to have been reserved for the cows and oxen which performed the farm labor of ploughing and treading out the grain, and which served also for food and religious sacrifices. There is little evidence of efforts to improve breeds. Cows were kept to maintain the supply of oxen; their milk-giving ability was small, owing in part to the inferior pasturage and their constant labor. For the same reasons the cattle were small and short-limbed, but tolerant of the harsh conditions.[60] The regulations of Leviticus, which exacted victims without blemish for sacrifice in the temple, may have been an adroit priestly method to encourage discriminating breeding; but this was possible only to a limited degree, since the majority of the stock ran free on the highland or lowland pastures.

Horses in Palestine.—Nowhere else were horses so great a luxury as in Palestine. Before the Jewish conquest, the Philistines of the coastal plain had numerous horses and chariots,[61] and so had the Canaanites who occupied the plain of Esdraelon and the moist lake-basin of Merom;[62] but the native tribes of the upland seem to have had none. When the Israelites invaded Palestine and established themselves on the rugged Judean plateau, they saved the cattle taken in their conquest, but were instructed to hamstring the horses,[63] because the land afforded no suitable pasturage. The earliest laws, embodied in the book of Deuteronomy, were the result of about three centuries of practical experience in Palestine. They forbade the kings to breed horses or to import them from Egypt for breeding purposes.[64] But later, when David and Solomon had extended the frontier of their domain from the Mediterranean coast to the Arabian Desert, and northward to the great bend of the Euphrates, the pasturage situa-

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57 Libbey and Hoskins, The Jordan Valley and Petra, vol. I, pp. 107–8. N. Y. 1905.

58 Deuteronomy, III, 7–8.

59 Numbers, XXXII, 1–5.

60 Hastings, Dict. of the Bible, art. Food.

61 Judges, I, 19.

62 Joshua, XI, 4–7, 14.

63 Joshua, XI, 9, 14.

64 Deuteronomy, XVII, 16.

tion was improved, because the kingdom included the plains of Sharon, Esdraelon, and Coelo-Syria, the broad fertile valley between the Lebanon and Anti-Lebanon Mountains, which provided both natural and irrigable meadows.

David deviated from the old rule after his victory over the northern Syrians by reserving from the booty horses for a hundred chariots[65] or probably three hundred animals. All the rest he disabled. Solomon went into horse-breeding on a large scale and made it a royal monopoly.[66] He received both horses and mules as tribute, doubtless from Gilead and Damascus, where the kings had chariots[67] and also from the northern Syrians; and he imported from Egypt droves of horses at a cost equivalent to $100 per head, to supply the cavalry and chariot corps of his army,[68] which was enlarged to protect the wide frontiers of the new Empire. From this time horses were royal beasts, associated with war. They were chiefly stall-fed on barley and straw.[69] The temporary expansion of the Jewish kingdom to the Mediterranean gave Solomon control of the great caravan route along the maritime plain, and made him the sole middleman in the horse trade between Egypt and the Syrian and Hittite kings of the north.[70] The Tel Amarna letters indicate that these rulers made an active demand for the Nile horses, which were doubtless a superior breed. Solomon also purchased stallions from Cilicia, probably to sell them again to Egypt to improve the strain there.[71] Lowland Cilicia, located between Mt. Amanus and the Taurus system, was a broad, well-watered alluvial plain, abounding in marsh meadows. As its tribute to Darius the Persian in 500 B. C. consisted of 360 white horses,[72] its equine breed was probably superior. After the division of the Jewish kingdom, the plains of northern Palestine or Israel continued to raise horses, but rugged Judea had to rely on importations from Egypt, despite the protests of the prophets.[73]

STOCK-RAISING IN PHOENICIA AND SYRIA.—Narrow, rugged Phoenicia, with its terraced mountain sides devoted to gardens and orchards, offered little feed or pasturage for animals, and little opportunity for their employment. Hence cities like Tyre and Sidon imported sheep

65 II Samuel, VIII, 3–4.

66 I Kings, X, 25–26.

67 II Kings, IX, 16, 20; V. 9.

68 I Kings, X, 28–29. II Chronicles, IX, 28.

69 I Kings, IV, 28.

70 I Kings, X, 28–29.

71 Maspero, Struggle of the Nations, pp. 215–216, 739–740. N. Y. 1897.

72 Herodotus, III, 90.

73 Isaiah, XXXI, 1. Ezekiel, XVII, 15.

and goats from the nomad tribes of Kedar in northern Arabia, and wool from Damascus. From Armenia (Togarmah) they bought war horses and mules,[74] which they probably sold again farther south in Palestine or Egypt. Armenia was a famous horse-breeding region in ancient times and used to pay to the Persian kings an annual tribute of 20,000 foals[75] which fed on its high Alpine pastures in summer, and in winter on the produce of its fertile valleys, as the horses of the wandering Kurds do today. The hinterland of the Phoenician seaboard was Coelo-Syria or the Lebanon trough, which afforded the largest and best pasture area of all Syria. The trough, which forms a broad U-shaped valley of gentle gradient, is drained by the Leontes and Orontes rivers, which rise in a swampy, indeterminate watershed near Baalbek at an altitude of 3,500 feet. The Orontes, the longer stream, takes a leisurely course northward through an almost level plain, and at intervals spreads out in broad shallow pools, bordered by marshes,[76] which in ancient times created extensive meadows for horses and cattle. Reclaimed in part for irrigated fields, the plain fed the ancient populations of Kadesh, Hemesa (Homs), Hamath, Apameia and Antioch.[77] After Alexander's conquest of Syria, the wet meadows formed by the Orontes near the city of Apameia were selected for the royal Macedonian stud-farm, which kept 30,000 brood mares and 300 stallions.[78] This is part of that Syria whose chariot and cavalry forces wrought havoc among the armies of the Kingdom of Israel.

Stock-raising in Asia Minor.—Asia Minor, owing to its more northern location, its peninsula form and high elevation, had a well assured rainfall along its coasts, especially on the west and north where the precipitation ranged from 25 to 40 inches (625 mm. to 1,000 mm.). In the mountain rimmed interior of the plateau, steppes and salt deserts prevailed, where cattle, wild asses and sheep roamed at large over dry or saline pastures,[79] or in summer ascended the inner valleys of the encircling mountains as they do today.[80] The products of this semi-arid hinterland were probably one source of the fine wool which through the ages has sought the industrial cities of the Aegean littoral and supported their textile industries. Phrygia Major, which lay just east of Lydia at the head of the mountain valleys opening westward

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74 Ezekiel, XXVII, 14, 18, 21.

75 Herodotus, V, 49. Strabo, XI, ch. XIV, 4, 9.

76 E. Banse, *Die Turkei*, pp. 315, 333-338. Braunschweig, 1916.

77 Mommsen, Provinces of the Roman Empire, vol. II, p. 148. N. Y. 1887.

78 Strabo, XVI, ch. II. 10.

79 Strabo, XII, ch. II, 7, 9; ch. III, 8; ch. VI, 1.

80 Banse, *Die Turkei*, pp. 98-114.

to Aegean winds, got hardly less rain than the coastal belt (400-500 mm.),[81] and therefore, Herodotus says, was famous for its wheat and cattle among the ancient Greeks of Ionia and the Carian seaboard. Cappadocia comprised the high eastern portion of Anatolia, 3,300 feet or 1,000 meters, and included in its area the lofty *massif* of Mount Argaeus (13,000 feet or 4,000 meters), an old volcano, whose lower slopes and piedmont, covered with a rich soil of weathered trachyte, tufa, and lava, merge into the fertile fields and meadows of Caesarea.[82] This region produced the immense number of horses, mules and sheep sent yearly as tribute to the Persian kings, and the famous Cappadocian race-horses of the Roman Circus.[83]

Western Asia Minor was a part of the ancient Aegean world, so far as its broad embayed littoral was concerned. Its early activities in stock-raising are therefore interwoven with those of the Greek people, by whom it was colonized. In the Iliad and Odyssey, horses and cattle belonged to sedentary agriculture, which presupposed irrigated fodder crops and wet meadows, and they therefore shared the honor due to the highest civilization of Homeric times.[84] But their distribution around the Aegean circle of lands shows a close connection with geographic conditions. Saturated river lowlands, deltaic flats, and lacustrine basins seem to produce horses and cattle as naturally as the reeds growing in the moist soil. In such places were found the flowery meadows and level stretches of rich soil which the Homeric Greeks loved for their cattle and horses.[85] Beside every green pasture was the meandering brook or reedy pool, recalling the *prata recentia rivis* of Vergil.[86] " The kine that are feeding innumerable in the low-lying land of a great marsh " give us the typical picture,[87] or the horses of Achilles " cropping clover and parsley of the marsh " on the Troad coast.[88] Of a Trojan prince we are told, " Three thousand mares with their colts had he, that pastured along the marsh meadow," where the Simois and Scamander rivers had deposited their silt on the flat coast,[89] forming swamps and lagoons about their obstructed outlets.[90] Enops tended " his herds near the banks of the Satnoeis,"

81 Ibid. p. 114.

82 Ibid. pp. 98-104.

83 Strabo, XI, ch. XIII, 8; XII, ch. II, 10. O. Keller, *Die Antike Tierwelt,* Vol. I, p. 225. Leipzig, 1909.

84 A. G. Keller. Homeric Society, pp. 20–21, 33–37. N. Y. 1902.

85 E. Buchholz, *Homerischen Realien,* vol. II, pp. 137–139. Leipzig, 1881.

86 Vergil, Aen. VI, 674.

87 Iliad, XV, 630–632.

88 Iliad, II, 775.

89 Iliad, XX, 221–222.

90 Strabo, XIII, ch. I, 31, 36.

where this stream watered another meadow for the horse-taming Trojans.[91] Farther south on the Aegean coast of Asia Minor, Homer observes " the wild geese or cranes or long-necked swans on the Asian meadow about the streams of Cayster,"[92] where the river meanders through its alluvial plain to the sea.

The Troad and Phrygia Minor to the north, located between the Aegean and the Propontis or Marmora, receive rain-bearing winds from both seas. Especially the Pontic clouds condense on the successive tiers of east-and-west ranges, which increase in altitude towards the high crests of Mount Ida and the Mysian Olympus in the south. A rainfall of 32 inches (800 mm.), fertile valley floors of alluvium, rich moist meadows, and swampy lakes formed by the streams dammed by the coastal hill ranges, combined to make admirable conditions for tillage and stock-raising here in ancient times as today.[93] Therefore Abydos and Percote on the Hellespontine shore had " pastures for swift mares " and for oxen;[94] and the Adrasteia plain, through which the Granikos flowed, was a natural pastureland praised by Homer. Nearby " many-fountained Ida,"[95] exposing a long flank to the Pontic winds and rains was wont to echo with " the lowing of herds and the bleating of sheep."[96] Farther east Asia Minor presents a continuous front of high forested mountains to the Pontic winds; but wherever a longitudinal trough like the Salon valley of northern Bithynia provided a level surface, or a river like the Iris or Phasis succeeded in building a small delta on this steep coast, where nature's irrigation overcame the summer drought,[97] there we hear of highly valued pastures for cattle and horses, of cows famous for their milk,[98] and of choice cheeses which entered the markets of the Mediterranean world.[99] So rare were good pastures that they were never overlooked by the ancients, even though small in area. Significant is the fact that these ancient meadows are districts of cattle production today. Such is the ancient Salon or modern Boli valley of Bithynia.[100]

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[91] Iliad, III, 250; XIV, 443.

[92] Iliad, II, 460–461.

[93] Banse, *Die Turkei*, pp. 65–71.

[94] Iliad, II, 819; XV, 546.

[95] Iliad, XIV, 283.

[96] Sophocles, Niobe, quoted in Strabo, XII, ch. VIII, 21. Iliad, II, 749; V. 315; XXI, 448.

[97] Strabo, XII, ch. III, 15.

[98] Aristotle, *De Animalibus*, III, ch. XXI, 17.

[99] Strabo, XII, ch. V, 7. Pliny, XI, ch. 97.

[100] Banse, *Die Turkei*, p. 80.

Horses in Thrace.—Thrace was famous for its horses from Homeric times. The great quarternary plain of eastern Thrace was probably too dry in the summer, as it is today, to provide proper pasturage for horses. However, the long southern littoral from Lake Stentoris and the mouth of the Hebrus River (Maritza) west to the Axius (Vardar) was a succession of lakes, lagoons, marshes, and brackish pools, and of alluvial lowlands, flooded at intervals by the mountain streams draining from the lofty Rhodope highlands,[101] and possessing every geographical feature for wet pastures. Diomedes, whose horses figured in the Trojan War and in the adventures of Hercules, ruled over the plain of Lake Bistonis with its city of Abdera, a region lying so low that Hercules was able to flood it by cutting a canal to the sea.[102] The horses of the Thracian Rheseus were the finest, swiftest and whitest ever seen by Trojan or Greek. Two herds of chestnut horses formed part of the dowry of a daughter of King Cotys of Thrace in the 4th century B. C.[103] Cavalry constituted an important feature of the Thracian army from the time of the Peloponnesian War down to that of the Roman Caesars, and made it a valuable ally in war.[104] In Strabo's time the Thracian cavalry numbered 15,000, and the infantry 20,000, an unusual proportion.[105] Thracian horses were early imported into Italy and Sicily, and the peculiar markings of the Thracian breed were well known.[106] White horses were brought to Rome for sacrifices and also to carry the victorious consuls in the public triumphs. After the Macedonian conquest, Thracian cavalry was incorporated in the mounted forces of Philip the Great, which were already strong. For Macedon has ample meadows in the broad alluvial plain of the Axius River, and excellent summer pastures in the northern mountains, whence came the Paeonian cavalry. Moreover, Philip imported 20,000 fine mares (*Nobilium equarum*) from the lower Danube Plains to improve his stock and probably introduced Thracian, Thessalian and Epirote strains for the same purpose.[107]

Stock-raising in Greece.—In Greece proper only a few localities afforded suitable pastures for horses and cattle, especially in the more arid eastern part of the peninsula, which was cut off by mountain ranges from the rain-bearing winds from the west. In this populous and progressive eastern part, cattle or their products were imported from the

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101 Herodotus, VII, 58, 109, 124.

102 Iliad, XIV, 225-227. Strabo, Fragment, 44, 47, 48.

103 Athenaeus, Bk. IV, 7.

104 Mommsen, Provinces of the Roman Empire, vol. I, p. 226. N. Y. 1887.

105 Strabo, Fragment, 48.

106 Vergil, Aen. V, 565.

107 O. Keller, *Die Antike Tierwelt*, Vol. I, p. 227. Leipzig, 1909.

steppes of far away Scythia, Africa and from Macedonia[108] to supply the local demand. The best and largest pastures were to be found in the broad lacustrine basin of Thessaly, which was alternately flooded and drained by the Peneus River system. This region repeatedly furnished cavalry for Athens from the days of Pisistratus,[109] and provided horsemen for Alexander's army in his conquest of Asia. In all Greek wars its alliance was sought because of its mounted troops. The Thessalian horse was a superior animal, the product of good feeding, of broad artificial selection made possible by large numbers, and of free movement over wide plains, whether he was grazing, training for races, or practising in cavalry manoeuvers. Therefore Sophocles makes Orestes enter the Pythian Games with a span of Thessalian steeds. A Thessalian stud farm at Pharsalus, on the southern margin of the lacustrine basin, bred Alexander's famous horse Bucephalus.[110] Aristotle in his Politics attributed the strong oligarchy which always ruled Thessaly to the adaptation of the country to horse-breeding, and the consequent concentration of cavalry forces in the hands of rich landowners. Homer praises "the oxen, horses and harvests of deep-soiled Phthia"[111] whose pastures bred the steeds of Achilles. This region comprised the shelving coast of the Pegasae Gulf and the alluvial valley of the Sperchius River, whose broad flats along the sea, always soaked and always growing by annual accretions of silt farther out into the Malic Gulf, must have furnished excellent wet meadows for the ancient war-lord as for the peasant of today. Across these fens of the Sperchius the modern carriage road runs for five miles on the top of a dyke, pierced at intervals to let the distributaries flow out to the sea, whose low shoreline is faintly visible several miles to the east. The growth of the half-fluid soil went on in Homeric times as today and provided perennial meadows. The scene embossed on the shield of Achilles may have been taken from his home country. It depicted a herd of kine: "lowing they hurried from the byre to pasture beside a murmuring river, beside the waving reeds," invariable marks of swamp vegetation.[112]

Horses in Hellas.—Aside from the Sperchius valley plain, which was the borderland of ancient Thessaly, Hellas proper could show only one region of excellent pasturage, and that was the moist lacustrine basin of Boeotia. Its early preëminence in horse breeding was based upon the rich pastures of "grassy Haliartus" on the reed-grown

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108 Herodotus, VII, 126. IV, 1-12. Polybius, IV, 38.

109 Herodotus, V, 63. Thucydides, I, 102, 107; II, 22.

110 Arrian, Anabasis, V, 19, 5.

111 Iliad, I, 154.

112 Iliad, XVIII, 573–576.

margin of Lake Copais,[113] and "Graia and Mycalessos with their wide meadows" in the valley of the River Asopus.[114] Therefore Boeotia was chief "of all the lands far-famed for goodly steeds."[115] This reputation, voiced by Sophocles, is repeated three centuries later by Dicaearchus.[116] And Thucydides states that only Boeotia, Phocis and Locris furnished the cavalry of the Spartan allied forces during the Peloponnesian War.[117] Phocis comprised the northern portion of the fairly broad valley of the Cephissus River, which continues southward as part of the Boeotian plain. It is rather a significant coincidence that the author, in a recent motor trip through Greece, met groups of horses only in Boeotia, the Cephissus valley of Phocis, and in Thessaly. The cavalry of Locris must have depended upon the small but fertile coastal plain of Opous along the Euboean Sound. The location of these cavalry states was ominous for Greece. At the battle of Plataea, as described by Herodotus, the allied Hellenic states had no mounted troops, because the invading Persians conquered or conciliated all the "horse" country to the north through which they marched.[118] Attica, as we have seen, had no pasture land and very slowly developed a limited force of cavalry. The conquest of the lower Asopus plain from Boeotia and the acquisition of the island of Euboea with its good pastures, once famous for their horses and cattle,[119] may have helped Athens maintain its thousand horsemen.

Stock-raising in the Peloponnesus.—The Peloponnesus contained little territory suited to cavalry movements. This fact partly explains the scarcity of mounted troops in the peninsula, whose wars were largely border conflicts along the high mountain boundaries of the several states. Such were Sparta's wars with Messenia, Argolis and Arcadia. "Argos pasture land of horses," which comprised the small silted plain at the head of the Argolic Gulf, and the valleys of Homeric Sparta, which included both Laconia and Messenia, were famous for their meadows and their equine stock.[120] The boy Telemachus, coming from the rugged isle of Ithaca, admired Sparta's "open plains where clover is abundant, marsh-grass and wheat and corn and

113 Theophrastus, *Historia Plantarum*, IV, ch. X, 7. Iliad, II, 503. Strabo, IX, ch. II, 18.

114 Iliad, IV, 499. Strabo, IX, ch. II, 10–11.

115 Sophocles, Edipus Colonus, 668.

116 Quoted in J. G. Frazer, Pausanius, Introduction, p. XLV. London, 1898.

117 Thucydides, II, 9.

118 Herodotus, IX, 19–29.

119 Ibid. V, 77.

120 Iliad, III, 74; IV, 530.

white-eared barley,"[121] and he received from King Menelaus a pair of horses as a gift. But the valley plain of the Eurotas River contains only about 40 square miles of level land "lying low amid the rifted hills;" it is shut off from the sea by a broad limestone ridge through which the little stream has cut its course to the Laconic Gulf. This plain had to suffice for both plough and pasture land for the Spartans of the historical period, till they conquered Messenia about 600 B. C.

It is easy to see the growing pressure of population upon the limits of subsistence in this secluded valley, the consequent substitution of hoplites or spearmen for cavalry as the main force of the Spartan army,[122] and the conquest of Messenia as a piece of necessary territorial expansion, all at about the same time. In this connection consider the further fact that the Eurotas valley, lying far south and in the rain-shadow of the lofty Taygetus Mountains, receives only 20 inches of rain (500 mm.) and endures four months of summer drought. Significant is the fact that the first Messenian war arose from a border quarrel, evidently about some pastures on a high, water-soaked moor (a common Alpine phenomenon), located west of the Taygetus crest, where the Spartans had set up a shrine or temple to Artemis Limnates or Artemis of the Marshes,[123] possibly to sanction their encroachment on Messenian territory. This Artemis was a goddess of fertility, worshipped in swampy or moist alluvial spots which were conspicuous by their succulent green herbage in the dry brown landscapes of the Greek summer.[124]

Messenia's extensive alluvial plains and her location on the windward side of the Taygetus range insured for her fairly abundant moist meadows. Here were " grassy Hira, divine Pharae, and Antheia deep in meads " all located on the deltaic flats along the Messenian Gulf.[125] The modern Kalamata, on the site of ancient Pharae, gets an annual rainfall of 39 inches (980 mm.),[126] and occupies a plain irrigated by the Nedon River, draining from the Gomo peak (4,165 feet or 1,277 meters) of the Taygetus range. Therefore ancient Messenia was famous for its cattle and horses.[127] We even hear of its selling a shipload of horses to Egypt in the third century B. C.[128]

Messenia shared the advantage of an ampler rainfall, coupled however with a long summer drought, with all western Peloponnesus and

121 Odyssey, IV, 602–604.

122 J. B. Bury, History of Greece, p. 129. London, 1909.

123 Tacitus, Annals, IV, 43. Pausanius, III, ch. VII, 4; IV, ch. XXXI, 3.

124 M. P. Nilsson, Griechischen Feste, pp. 214–216. Leipzig, 1906.

125 Iliad, IV, 291. Strabo, VIII, ch. IV, 1, 5.

126 A. Philippson, *Europa*, p. 284. Leipzig, 1906.

127 Strabo, VIII, ch. V, 6.

128 Polybius, V, 37.

Hellas north to the Gulf of Ambracia (Arta) and the borders of Epirus, where summer showers begin. The broad Tertiary plain of Elis, watered by the Alpheus and Peneus rivers, and dotted with lagoons along its coastal belt, contained the best lowland pastures of the Peloponnesus.[129] Here grazed the cattle from the stables of King Augeus and the famous horses of Nestor of Pylus,[130] the king who in a cattle raid on the neighboring city of Elis drove off 50 herds of kine, 50 flocks of sheep, 50 flocks of goats, and 150 mares with their foals.[131] There followed a punitive expedition by mounted Eleians and a battle in which horses and chariots were part of the booty,[132] fought out on the level plain of the Alpheus. When Philip V. of Macedon invaded the Peloponnesus in 218 B. C. and violated the sanctity of sacred Elis, he secured an immense amount of cattle.[133] Today, the little town of Gastouni near the mouth of the Peneus, only six miles from the ancient capital city of Elis, is the chief cattle market of the Peloponnesus. Thus closely does the prosaic present link itself with the heroic past. Thus persistently operate the geographic factors in history.

The highland core of the Peloponnesus, the plateau of Arcadia, contained several small lake basins with katavothra drains, subject to flooding after winter rains and spring thaw of the snow on the surrounding mountains. These afforded fine meadows, as the central pool contracted with the continued drought of summer, leaving a girdle of verdure behind. The lake plain of Orchomenus was mostly mere,[134] owing to the drainage from the surrounding heights; on the plain of Pheneus, according to tradition, Odysseus kept his mares on pasture.[135] All Arcadia became famous for its sheep, asses, horses and cattle.[136] Rugged mountain relief excluded horses and cattle from the small islands of Greece, but admitted sheep, goats and swine, where the forest yielded mast. Telemachus describes his native Ithaca as having "no open runs, no meadows, a land for goats and pleasanter than grazing country. Not one of the islands is a place to drive a horse, none has good meadows of all that rest upon the sea."[137] Therefore Odysseus pastured his goats and some of his swine on the home island,

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129 Theocritus, Idyls, XXV.
130 Iliad, XXIII, 202–203.
131 Iliad, XI, 671–680.
132 Iliad, XI, 707–723, 739–747.
133 Polybius, IV, 75.
134 Pausanius, VIII, ch. XIV, 1–4.
135 Ibid. VIII, ch. XIV, 5–6.
136 Varro, II, ch. I, 14; ch. IV, 12; ch. VI, 2; ch. VIII, 3.
137 Odyssey, IV 604–608; XIII, 241–246.

but sent his twelve herds of cattle and his flocks of sheep to pasture on the broad alluvial lowlands of Acarnania and Aetolia on the opposite mainland.[138] An Ithacan nobleman kept a stud-farm of twelve mares across the strait in Elis, where he bred mules.[139]

STOCK-RAISING IN EPIRUS.—Farther north on this western front of Greece lay Epirus, with high lake plains tucked away between its wooded mountain slopes, receiving 40 inches of rain (1,000 mm.) or more annually and getting thunder storms till mid-summer. Though located on the sunset side of Greece, far from the morning foci of Hellenic culture, the fame of its pastures and herds penetrated eastward, because it contained the Pelasgian sanctuary of Dodona. So Hesiod sang: "There is a land Ellopia with much glebe and rich meadows, abounding in flocks and shambling kine. There dwell men who have many sheep and many oxen. . . . And there upon its border is built a city Dodona."[140] The sanctuary lay on the southern margin of the katavothra pool, Lake Ioanina, which in ancient as in modern times was bordered by wet meadows, while the whole valley of Ioanina, 20 by 7 miles in extent, was one immense plain of pasture,[141] free from the encroachments of a too dense population. The cattle of Epirus were the finest of Greece, better than those of Italy, and therefore they were exported to improve the strains on Roman farms.[142] Aristotle states that Epirus raised very large cows which gave one and one-half amphora or ten gallons of milk daily; and that these cows, which required much pasture, could be changed to fresh grazing every hour, so abundant and excellent was the meadow land.[143] The oxen too were very large. Epirus pastured also the King's herds of huge Pyrrhic cattle which could not live, or more probably deteriorated, when removed to other countries.[144] Today the pasture lands of Epirus, still excellent and much extended by deforestation, support a considerable cattle and horse-raising industry.[145]

SHEEP AND GOATS IN GREECE.—Goats and sheep were regular adjuncts of ancient Greek farms like the homestead of Odysseus; but in summer they went to "the high meadows of the pasturing flocks."[146]

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138 Odyssey, XIV, 13, 99–103. Strabo, VIII, ch. VIII, 1.

139 Odyssey, IV, 634–635.

140 Hesiod, Catalogue of Women and Eoiae, 97. Loeb Lib., London, 1914.

141 W. Leake, Northern Greece, vol. IV, pp. 131–135, 168–173, 184–200. London, 1835.

142 Varro, II, ch. V, 10. Strabo, VII, ch. VII, 5, 12.

143 Aristotle, *De Animalibus*, III, ch. XXI.

144 Aristotle, *De Animalibus*, VIII, 7.

145 Philippson, *Thessalien und Epirus*, p. 279. Berlin.

146 Sophocles, *Edipus Rex*, 1103.

The shepherd in Sophocles' *Edipus Rex,* when asked where he dwelt, replied: "Now t'was Kithaeron, now on neighboring heights." And again: "He needs must know when on Kithaeron's fields, he with a double flock and I with one, I was his neighbor during three half-years, from spring until Arcturus rose; and I in winter to my own fold drove down my flocks, and he to those of Laios" (in Thebes).[147] These mountain pastures were inter-state boundary zones, where shepherds and flocks from the two sides mingled every season. Here it was easy to spirit away a child across the border to an asylum in some shepherd's cot beyond, as was done with the infant Edipus, rather than incur the moral responsibility of exposing him to the wolves.

The breeds of sheep and goats were selected for the improvement of the wool and hair. Cattle rearing too was conducted in Greece on scientific principles. Choice animals were reserved for breeding purposes, and the strain was improved by the importation of superior foreign kinds.[148] Aristotle states that the oxen and sheep of Greece were smaller than those of Egypt, though he seems to make an exception of the Epirote cattle.[149] In this connection, the fact is significant that Xerxes found the Thessalian horses, which were the best of all Greece, distinctly inferior to the Persian animals.[150] This may mean that horse-raising in Greece suffered from small numbers and excessive in-breeding, which frequently results in dwarfing; while the stud-farms of Babylonia comprised enormous numbers of animals. The cob type of horse depicted in the frieze of the Parthenon may be the far-off artistic effect of a geographic cause.

Mountain Pastures in Italy.—The location of Italy farther west and north than the lands of the Eastern Mediterranean Basin insured the peninsula a heavier rainfall and therefore better grazing.[151] Its relatively extensive coastal lowlands and river plains afforded larger areas for wet meadows than were found farther east, except in Egypt. The Alps, with their frequent summer showers and extensive growths of deciduous trees, furnished excellent highland pastures in the hot season. The Apennines, owing to their ample precipitation (35 to 50 inches), their long western slope facing the rain-bearing winds, and the top dressing of volcanic soil covering much of their valley floors, yielded fair or even excellent grazing for horses and cattle

147 Ibid, 1127, 1135–1139.

148 Blümner, Home Life of the Ancient Greeks, p. 497. London, 1895.

149 Aristotle, *De Animalibus,* VIII, ch. XXVII, 5.

150 Herodotus, VII, 196.

151 Strabo, III, ch. V, 1.

during the summer droughts, and thus supplemented the winter pastures on the plains. Geographic conditions in Italy therefore favored the development in ancient times of organized pastoral husbandry on a big scale, many phases of which have persisted to the present, despite the deterioration of the Apennine pastures in consequence of forest denudation. Before the Punic Wars, as now, flocks and herds were driven every spring from the plains of Apulia to the public grazing grounds in the mountains of Samnium;[152] and in autumn they descended again to the lowlands, to feed upon the meadows, reviving with the fall rains, or upon the stubble of the grain fields. In these seasonal migrations through the centuries they beat out broad, grassy tracks, the ancient *calles publicae,* which survive in the modern *tratturi* used today by the nomad herders.

During the last two centuries of the Roman Republic, stock-raising on big hill or mountain estates (*saltus*), varying in size from 800 to many thousand *jugera* (500 acres up) began greatly to overshadow tillage.[153] The term *saltus* came to be applied indifferently to a highland pasture and a mountain range or *massif,*[154] like the *Saltus Ciminius* of Etruria and the *Saltus Vescinus* on the border between Latium and Campania. The animals raised were chiefly sheep, goats, and swine; in a less degree cattle, horses, mules, and asses, for whom suitable pasturage was in general less abundant.[155] However, the brushwood and leafage of the hill pastures, where groves of deciduous trees abounded, made a welcome and wholesome change to horses and cattle from the grass of the lowlands, and constituted one advantage of the transfer from the winter grazing land.[156] Another factor in the improvement may have been the escape from the mosquitoes and flies of the plains.

Cattle, horses, and mules of inferior breeds were raised in the Ligurian Apennines, where a rainfall of 50 inches (1,250 mm.) insured unfailing pastures, and were sold in Genoa whence they were exported to Rome.[157] In the extreme south of Italy, the high plateau-like range of Sila Mountain stretching through the length of Bruttium rises high enough (Sila Forest 6,330 feet and Aspromonte 6,420 feet) to get a rainfall rivalling that of the Alpine piedmont (43.3 inches

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152 Varro, II, ch. I, 16; ch. II, 9.

153 Mommsen, History of Rome, vol. III, p. 74. N. Y. 1905.

154 Catullus, XXXIV, 11.

155 E. Speck, *Handelsgeschichte des Altertums,* vol. II, part II, p. 240. Leipzig, 1901.

156 Varro, II, ch. II, 10.

157 Strabo, IV, ch. VI, 2.

at Cosenza).[158] It was therefore covered with forests and pastures, frequented by flocks and herds. "On mighty Sila feeds the lovely heifer," sang Vergil.[159] The cheese of the region was famous, "recalling by its taste the fragrant herbs on which the cattle browsed."[160] On the eastern slope of Sila Forest, in the valley of the Neaethus (modern Neto), Theocritus staged the meeting of neatherd and rustic in his fourth idyl. Today thousands of horses, cattle and sheep crop the summer herbage of the Sila pastures,[161] tended by rougher herdsmen than those who piped to the Greek Theocritus. Sicily presented a happy combination of upland pastures and moist, lowland meadows,[162] which made it a home of horse-breeders and cattlemen from early times. Horses and mules from Syracuse, Aetna, Acragas and Kamarina took prizes in the Sacred Games of Greece from 494 B. C.,[163] and cavalry forces were always at hand for the Tyrants of Syracuse.[164] The Roman conquest saw the whole interior of Sicily converted into vast grazing estates. The official plunder of the Proconsul Verres comprised "herds of the noblest mares."[165]

THE WET PASTURES OF ITALY.—Italy had numerous wet pastures unreclaimed or unreclaimable for tillage, like the Fenland of England and the polders of Holland. The depressed area of northern Apulia, located between the Apennines and Monte Gargano, was a lake-strewn lowland of immature drainage underlain by hard limestone, which was impenetrable to the roots of trees.[166] Useless for orchard or vineyards, and flooded by the Apennine torrents from October to June, it served well for pasture land.[167] Greek legend associated the region with Diomedes, the great horse-fancier, and told of his attempts to control the inundations by cutting a canal through the lowland to the sea. The founding here of Argos Hippium or "horse-breeding Argos,"[168] which survived as the Roman town of Arpi, coupled with the legend of Diomedes, points to marsh pastures, which Greek colonists

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158 W. Deecke, Italy, pp. 82, 428–431. London, 1904.

159 Vergil, Georgics, III, 219.

160 *Cassiodori Variae*, II, 9–13.

161 Gael-Fells, *Unter-Italien*, p. 721.

162 Theocritus, Idyls, *passim*. Strabo, VI, ch. II, 3.

163 Pindar, Odes, Olym. I, III-VI. Pyth, I, II, III, VI. Diodorus Siculus, VIII, 82.

164 Thucydides, VI, 20.

165 Strabo, VI, ch. II, 6, 7. Cicero, Verres, II, 7, 20.

166 Deecke, Italy, p. 401. London, 1904.

167 Columella, VI, ch. XXVII, 2. Pliny, VIII, 154.

168 Strabo, VI, ch. III, 9.

exploited and drained by ditches during the winter floods. Here arose the Apulian breed of horses,[169] which was famous among the Romans.

Similar geographic causes and economic effects existed in the extensive marshes about the head of the Adriatic, which in summer afforded wide stretches of wet meadows. There the flood season was protracted long after the winter rains, owing to the slow melting of the Alpine snows; and there in a region of marshes, lagoons, braided streams, meandering rivers and deltaic distributaries, lived the ancient Veneti, from remote times famous for their horses. They let their equine herds pasture at large on the wet meadows, but branded each animal with its owner's name. Certain fine breeds of horses became established, and acquired a reputation even in Greece. The grazing was so excellent, that Dionysius, Tyrant of Syracuse, (d. 367 B. C.) kept his stud of race horses on these Venetian plains.[170] Similar conditions obtained over much of the level, well watered Po valley, where abundant irrigating streams, high water table, and occasional summer showers combined to keep the meadows green. There, on his father's Mantuan farm, Vergil knew the "wide pastures by the brimming river, where moss abounds and green herbage lines the banks;" and where brood mares and cows found the best grazing. There was the grass, the willow leaves, the marsh sedge and the standing grain which made the best fodder for growing oxen.[171] Countless irrigation streams, fed by Alpine rivers, kept the lush grass green throughout the hot season, and maintained the herds of cattle and the famous cheese industry of antiquity, much as they do today.

Wet meadows on a smaller scale were found in many longitudinal valleys of the Apennines, where the drainage was imperfect. Horace, on his frequent journeys to his Sabine farm up in the Anio valley, must have often seen these "grassy meads with winding streams and willows of the marsh."[172] He had one on his own estate which needed diking, because the winter or spring floods were sometimes excessive.[173] The Sabine country comprised also the Reate district with its excellent pastures, where Varro located his stud farm and where the famous Rosea breed of horses originated.[174] It lay in an old lake basin in the Sabine country, just where converging streams debouched upon the intermontane plain. Constant deposition of travertine, by the River Velinus, whose waters were impregnated with carbonate of lime, tended to dam the outflow, kept the valley floor too wet for tillage, and

169 Varro, II, ch. VII, 1. Columella, VI, ch. XXVII, 2.

170 Strabo, V, ch. I, 4, 5, 6.

171 Vergil, Georgics, III, 143–144, 175–176.

172 Horace, Odes, Bk. II, V, 1.

173 Horace, Epistles, Bk. II, XIV, 29.

174 Varro, II ch. VI, 1–2; ch. VII, 6; ch. VIII, 3.

finally flooded the Rosea pastures.[175] This necessitated a series of drainage canals, constructed through the centuries from 271 B. C., which reclaimed the Rosea plain for grazing.[176] In summer, the mules and asses of Reate were driven up into the neighboring mountains,[177] probably to release the Rosea meadows for hay crops. Similar valleys of immature or arrested drainage in Etruria and Umbria, like the lake-strewn course of the Clanis River and swampy course of the lower Arno in Etruria, must have provided the excellent meadows which, supplemented by the Apennine pastures, explain the good cattle and sheep, and the famous cheese of these districts.

Irrigated Fodder Crops in Italy.—The out-pastures of the mountains and marshes were abundantly supplemented by hay, clover, alfalfa and other fodder crops, maintained by irrigation through the summer, for the winter keep of the stock, especially the horses and work animals. Meadows were located preferably in rich valley or plain land. The soil, whether light and loose or stiff and heavy, was carefully tilled and regularly manured, especially on hillside fields. Marshy land, if in meadow, was drained by ditches and then irrigated at will.[178] Pliny urged that rain water from public highways should be diverted to the meadows, evidently because it contained soluble manure from the droppings of passing animals. Hay and clover fields were mowed in early June, irrigated, mowed again in August, and usually again in September or October. At Interamna in Umbria the farmers got four crops of hay a year,[179] as might be expected from the location of the place on a flood-plain peninsula between two streams. Lucerne or alfalfa fields regularly yielded six crops.

Even with this careful provision for fodder, animals were most economically fed. Cato recommended that the green leaves of elm, poplar, fig and oak trees, so long as they were available, should be fed to cattle and sheep, if hay were scarce;[180] that the straw of all grains, also of beans, vetch and lupines should be stacked in the barn for fodder, and grape husks preserved in jars for the same purpose; that mast gathered in the forests be soaked in water and fed to the oxen.[181] Chaff also, preferably that of millet or barley, was used as

175 Deecke, Italy, p. 102. London, 1904.

176 Mommsen, History of Rome, vol. II, p. 85. N. Y. 1905.

177 Varro, II, ch. VIII, 5.

178 Cato, *De Re Rustica,* VIII, XXVIII, LIII. Columella, II, ch. 2, 17, 18. Varro, I, 29.

179 Pliny, VIII, ch. 28, 67. Varro, I, 31, 33.

180 Cato, *De Re Rustica,* V, XXV. Pliny, VIII, 74.

181 Cato, *De Re Rustica,* XXX, LIV.

feed.[182] Moreover the allowance of oxen for tillage land was small, only one yoke for every 80 or 100 jugera,[183] despite the numerous ploughings both of fallow and crop fields.

Cattle raising was an important branch of stock farming in Italy, because cows or oxen yielded various products (meat, milk, hides and horns) and served as the chief work animals. Horses and mules were extensively used as draft animals, more than in Greece and Asia Minor; because land travel was better developed in Italy, luxury had reached a higher point,[184] and the supply of animals was greater, owing to more abundant pasturage. Nevertheless, the effect of the summer drought in restricting the supply of horses remained apparent. From 200 to 50 B. C. the export of horses from Italy was forbidden by law. Certain Gallic envoys from Istria and the neighboring Alps in 170 B. C. received special permits to export ten horses each,[185]—proof of the rigid control. The importance of the unfailing northern pastures for horse-raising is evidenced by a fact cited by Mommsen, namely, that in the Imperial Roman army the cavalry was Celtic, recruited pre-eminently from Trans-Alpine Gaul, with Gallic men, whose manoeuvers and technical terms were Celtic.[186]

Swine in Italy.—Swine production, which in the ancient Mediterranean world depended chiefly on mast-yielding forests, flourished in Italy, because climatic conditions permitted beech, oak and chestnut groves in nearly all parts of the peninsula. Pigs were raised on every landed estate.[187] They were fed mainly on the mast of the home woodland or the mountain forests,[188] and then fattened on barley and other grains to give the meat various flavors.[189] Beechnut bacon was a commonplace in Rome. No other country slaughtered so many pigs, for sacrifices, family use and the army commissary, according to Polybius. The chief supplies in his time (150 B. C.) came from the Po valley, whose northern location and encircling mountains ensured the late spring and early summer rains necessary to maintain abundant mast forests.[190] With the expansion of Roman power into Farther Gaul and the growing demand of the populace for imported food supplies,

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182 Pliny, XVIII, 72, 74.

183 Cato, R. R. X. Varro, I, ch. XIX, 1.

184 Blümner, *Römische Privataltertümer*, pp. 460–465. Munich, 1911.

185 E. Speck, *Handelsgeschichte des Altertums*, vol. III, part II, p, 284. Leipzig, 1901. Livy, XLIII, 5.

186 Mommsen, Provinces of the Roman Empire, vol. I, p. 116. N. Y. 1887.

187 Cicero, *De Senectute*, XVI, 56. Columella, XVII, 9.

188 Vergil, Georgic, II, 72, 520.

189 Varro, II, ch. IV, 3. Pliny, VIII, 209.

190 Varro, II, ch. IV, 10–11. Polybius, II, 15. Strabo, V, ch. I, 12.

this well forested northern province began shipping salt pork not only to Rome but to other parts of Italy. That from the Sequanian country at the head of the Saône valley had a great reputation.[191] The wooded slopes of the Pyrenees and rainy Cantabrian mountains of northern Spain also supported herds of swine, which furnished the basis for a lucrative native export trade in hams.[192]

Sheep in Italy.—Sheep-raising was widely distributed in ancient Italy, and it was semi-nomadic in its character, the flocks vibrating between the plains in winter and the Alps and Apennines in summer. The sheep producing the choicest wool, both as to softness, fineness and natural colors (white, black and tan), grazed on the leeward slopes of the Alps and Apennines, where the pastures were relatively dry. They were found in the south in ancient Apulia about Luceria and Canusium, in Calabria about Tarentum and Brundusium, in eastern Lucania and the nearby valleys of the Sybaris and Crathis.[193] Their superiority in this district may be attributed in part to the fact that they belonged to the fine Greek breeds imported by the original colonists of Magna Graecia.[194] In northern Italy also the finest fleeces came from the rain-shadow sides of the Apennines and Alps; from the *Campi Macri* in the northern Apennines between Parma and Mutina, whose fine toga wool ranked with that of Tarentum;[195] from western Liguria at the eastern foot of the Alps about Pollentia; and from the Venetian plain about Altinum, whose product ranked next to that of Apulia and Parma.[196] All the Po valley pastures produced coarse wool and goats' hair suitable for weaving rough cloth for mantles and slaves' dress. The finer yields were evidently a late development,[197] synchronous with the advance of civilization and movement of population into this colonial frontier district of Roman Italy. Significantly enough, all these regions of fine wool production have maintained their leadership into the present.[198]

The Improvement of Breeds.—At a time when the rainy lands of middle and northern Europe knew only uncontrolled stock-raising on the open range, Italy, like Greece, secured the largest financial

[191] Strabo, IV, ch. I, 2; ch. III, 2; ch. IV, 3.

[192] Strabo, III, ch. IV, 11.

[193] Horace, *Carmina*, Bk. III, XV, 13. Columella, VII, ch. II, 3; ch. IV, 1. Pliny, VIII, 190.

[194] Blümner, *Römische Privaltaltertumer*, p. 237. Munich, 1911.

[195] Columella, VII, ch. II, 3. Strabo, V, 218.

[196] Martial, XIV, 155.

[197] Columella, VII, ch. II, 3.

[198] L. W. Lyde, Continent of Europe, p. 94. London, 1913.

returns from its relatively limited pastures by improving its stock through artificial selection.[199] It laid great emphasis upon the choice of the best strains for breeding purposes. Horned cattle were imported from the Po valley and Epirus to improve the local breeds,[200] especially large cows from the Pyrrhic herds, which had a great reputation in Italy.[201] The Italian cattle, which were bred primarily for work animals, were strong but gave little milk. Hence it became usual to import good milk cows from the Alpine regions.[202] Significantly enough, the same thing is done today on a big scale to exploit the wet meadows along the Po River, which are devoted to dairy cattle. Swiss cows are imported since they yield more milk when fed on these irrigated pastures for ten months than do the native Italian kine,—700 as opposed to 550 gallons. This large milk production explains the modern trade in Parmesan, Gorganzola and Stracchino cheese which emanates from this region.[203] In ancient times the Apennines of Umbria, Etruria and Liguria were the chief districts of cheese production,[204] but the Alpine cheese of Narbonensian Gaul was the best, according to Martial.[205]

But the improvement of stock was not restricted to cattle. Fine mares of racing blood were imported from Thrace, Thessaly and Epirus,[206] asses for breeding purposes from Arcadia,[207] fine sheep from Attica and other parts of Greece,[208] and rams for covering from the Guadalquiver valley of Spain.

Narbonensian Gaul formed a connecting link geographically and economically between Alpine Italy and Pyrenean Spain, owing to location, relief and climate. The valley plain and deltaic flats of the Rhone furnished moist pastures[209] till July, just as they do today,[210] while the neighboring Alps and Cevennes Plateau furnished summer grazing. The abundance of cattle about Massilia was reflected in the low price paid for sacrificial oxen and young bullocks in the fourth century B. C. at the local Carthaginian temple, whose tariff of charges

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199 Vergil, Georgic, III, 156–161.

200 Varro, II, ch. V, 9–10.

201 Pliny, VIII, 176.

202 Columella, VI, ch. XXIV, 5. Pliny, VIII, 179.

203 G. C. Chisolm, Commercial Geography, p. 337. London, 1904.

204 Pliny, XI, 97.

205 Martial, XIII, 30, 31.

206 Vergil, Georgic, I, 59; II, 90.

207 Varro, II, ch. VIII, 3. Columella, VII, 1.

208 Varro, II, ch. II, 18. Columella, IV, 1.

209 Strabo, IV, ch. I, 7.

210 E. Reclus, Europe, vol. II, pp. 99-102. N. Y. 1883. Also personal observation in 1922.

has been preserved;[211] and it explains the ancient cheese export from Nemausus (Nimes) and the district of the Gabali,[212] famous for its cheese today.

STOCK-RAISING IN SPAIN.—In the rainy mountains of northern Spain, swine raising and the pork-packing industry were supplemented in the rugged provinces of Asturia and Gallacia by the breeding of sumpter mules, which answered the local need of transportation and were also exported to Rome.[213] On the steppes of the semi-arid Iberian plateau, large herds of wild horses pastured at large. They were fine swift animals, and explain the superiority of the native Iberian cavalry.[214] Hannibal had large numbers of African horses in Spain in 219 B. C., and he invaded Italy with 12,000 cavalry, chiefly Numidian but partly Spanish. In time, the Spanish breeds were greatly improved, because Spanish race horses competed in the Roman Circus with Cappadocian, Parthian and Armenian steeds in the first century of the Empire. Martial praises the horse racing at Bilbilis, on the northeastern rim of the Meseta. The economy of the highland tribes was primitive, based chiefly on a half-migratory agriculture and goat-herding, which was suited to their dry grass lands. Cattle-raising as an adjunct of sedentary tillage meets us only in Baetica in the tide-water plains of southwestern Spain, where Phoenician colonists early established themselves. There, in a region of scant rainfall (12 to 15 inches), the belt of littoral between the multiple mouths of the Guadalquiver and the Guadiana afforded natural meadows, which were watered both by meandering distributaries and flood tides. Those near Cadiz seem to have been communal pastures, probably owned by the city. The cattle grazing there were fat and yielded rich milk, but they were occasionally overwhelmed by the incoming tides.[215] The dry pastures of the Guadalquiver valley supported excellent sheep, whose wool was famous in the Roman world for its softness and color, especially the reddish-tan wool of the Corduba (Cordova) district.[216] The folded mountain ranges which enclose this valley on the south received enough rain for extensive forests of oak and other trees. These apparently sup-

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211 A. Boeckh, *Die Staatshaushaltung der Athener*, vol. I, p. 95.

212 Pliny, XI, 97.

213 E. Speck, *Handelsgeschichte des Altertums*, vol. III, part II, p. 283. Leipzig, 1901.

214 Strabo, III, ch. IV, 15.

215 Strabo, II, ch. II, 4, 5, 6; ch. V, 4.

216 Blümner, *Römische Privataltertümer*, p. 240. Munich, 1911.

ported herds of swine, for Strabo tells us that Mellaria (modern Tarifa) produced salted provisions and exported them to Tingis (Tangier) in Mauretania.[217] These salted provisions undoubtedly comprised pork products, though they may have included also salt fish.[218] On the northwest side of the Iberian Peninsula, where exposure to the Atlantic winds insured unfailing rains, there was ample pasturage all year round, both in the plains of the Tagus and Duoro and on the neighboring highlands. This is indicated by the abundance and cheapness of oxen, calves, pigs and sheep in ancient Lusitania (Portugal),[219] where the grazing conditions resembled those of northern Italy.

Stock-raising in Mediterranean Africa.—North Africa reproduces the climatic conditions of interior Spain and the Guadalquiver valley, with their attendant effects upon stock-raising. In the territory of ancient Carthage, cattle and horses were associated with tillage in the irrigable plains near the coast. There in the moist alluvial valley of the Bagradas River (Majerda River) the invading army of the Sicilian Agathocles (4th Century B. C.) saw cows, oxen and sheep grazing in the irrigated meadows, while "in the near-by marshes there were vast numbers of brood-mares."[220] The interior grasslands, lying in the rain-shadow of the Atlas ranges, were pastured by big herds of horses and cattle belonging to the nomads of Numidia and Mauretania.[221] These supplied the Numidian cavalry which formed an important part of Hannibal's forces in the Second Punic War, and constituted the major part of Massinissa's army, Scipio's ally, in the Roman campaign in Africa.[222]

Farther east, on the Cyrenaican coast of Africa, the plateau of Barca (elevation 2,000 feet or 610 metres) was high enough to condense winter rains in this otherwise arid belt, and therefore to support good but ephemeral pastures for horses and cattle back to the margin of the desert.[223] Springs issuing from the escarpment and base of the limestone highland irrigated fields and hay meadows. Hence the Greek colony of Cyrenaica enjoyed a great reputation for horse

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217 Strabo, III, ch. I, 8.

218 Strabo, III, ch. II, 6.

219 Polybius, XXXIV, 8.

220 Diodorus Siculus, XX, ch. I, 8.

221 Strabo, XVII, ch. III, 7, 9, 19. Mommsen, Provinces of the Roman Empire, vol. II, p. 368.

222 Polybius, III, ch. 35, 65, 68, 71, 72, 113, 114, 117; XV, ch. 3, 5, *et passim*.

223 Arrian, *Indica*, ch. 43.

breeding in antiquity.[224] Its kings frequently won the chariot races in the Greek Games and became the theme of many a Pindaric ode.[225] The colonists doubtless purchased horses from the neighboring nomads, whose route to the coast ran right past the city of Cyrene,[226] and then improved the animals by good feeding and training.

PASTORAL NOMADISM ON THE ARID MARGINS.—Horses and cattle, sheep and goats, formed the chief wealth of the nomads who hung on the semi-arid outskirts of the Mediterranean lands, and ranged widely in search of grass. Their animals drifted into the markets and stockfarms of the sedentary Mediterranean peoples in a dozen different ways,—by purchase at border trading-post or town, by capture during nomadic invasions or in the subsequent punitive expedition of the farmer nations, or by the employment of nomad cavalry as allies or mercenaries in war. This was especially the case with horses and cattle whose importation when full-grown worked an economic saving in countries of limited pasturage. As a corollary, this saving was greater, as a rule, in eastern Mediterranean lands than in western.

The sources from which such imports were drawn were not limited to the semi-arid regions to the south and east of the Mediterranean; they included the European steppes bordering the Black Sea and the well-watered districts north of the Alpine barrier. Cattle, hides and wool were regularly purchased by the ancient Greek traders from the Scythians of the Euxine coast,[227] and they were also imported into Italy from the upper Danubian plains by the passes of the Julian Alps and Carso Plateau.[228] Marine transportation of live animals presented no problem, as has been shown.

Thus the economic history of the Mediterranean lands can never ignore the factors of climate, relief, and the uniting force of the *Mare Internum.*

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224 Strabo, XVIII, ch. III, 2.

225 Pindar, Odes, Pyth, IV, V.

226 E. Curtius, History of Greece, vol. I, pp. 486-487. N. Y. 1867.

227 Ibid. vol. I, pp. 440–441.

228 Strabo, V, ch. I, 8.

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THE VEGETATIONAL HISTORY OF THE MIDDLE WEST

HENRY ALLAN GLEASON

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Part I

The Dynamic Viewpoint.—Many years have elapsed since Engler published his famous and fundamental "Leitende Ideen," which he had adopted as a basis for his discussion[1] of the Tertiary and Pleistocene development of the vegetation of the earth. Here, in thirty-six concise paragraphs, he summarized the general principles controlling the distribution of species and of species-groups. The first two of them serve as a summary for all:

"1. Die gegenwärtige Verbreitung der Pflanzen ist nicht blos bedingt durch die jetzt auf der Erde herrschenden klimatischen Bedingungen und die Bodenverhältnisse.

"2. Ein wahres Verständniss der Verbreitung der Pflanzen ist nur dann möglich, wenn man die allmälige Entwicklung derselben zu ermitteln sucht."

Engler was apparently inspired to his studies of vegetational history and development, at least in part, by the classic essays of Asa Gray.[2,3,4] His lead was followed by numerous European botanists, who, assisted by the co-operation of palaeontologists and glacial geologists, have in the past two decades contributed greatly to the knowledge of the phytogeographical history of central and western Europe. Later American botanists, on the other hand, neglected such lines of investigation almost completely and their phytogeographical activities were confined, as is natural in relatively new regions, to descriptions of floras and the determination of modern distribution. It remained for Adams[5,6] to revive developmental biogeography in America and to show that the distribution of a species can be satisfactorily explained only through the location of its origin and the nature of its subsequent migrations.

General Control of Distribution.—The distribution of plants, as shown by Engler's principles quoted above, depends, in general terms, on modern environment and earlier developmental history. Both

1 Engler, Adolph. Versuch einer Entwicklungsgeschichte der Pflanzenwelt, insbesondere der Florengebiete, seit der Tertiärperiode. Leipzig, 1879.

2 Gray, Asa. The flora of Japan. Scientific Papers 2: 125–141. (1859) 1889.

3 Gray, Asa. Sequoia and its history. Scientific Papers 2: 142-173. (1872) 1889.

4 Gray, Asa. Forest geography and archaeology. Scientific Papers 2: 204–233. (1878) 1889.

5 Adams, C. C. Southeastern United States as a center of geographical distribution of flora and fauna. Biol. Bull. 3: 115–131. 1902.

6 Adams, C. C. Postglacial origin and migrations of the life of the northeastern United States. Journ. of Geog. 1: 303–310, 352–357. 1902.

of these are intimately concerned with migration, the latter factor portraying its progress and the former its limitation. Neither factor alone can account completely and satisfactorily for the present range of any species. This is the resultant of its range at any period in the past and its opportunities for subsequent migration; one exposure in the long film of an activity which has been continued since the origin of the species. If logs in the glacial drift show that *Pinus Strobus* formerly existed in central Illinois and experiment proves that it can thrive there now, historical evidence must be used to show why it left: modern conditions may show whether and why it is not returning.

Vegetational History and Human History.—The history of the vegetation of the Middle West, as of every other portion of our continent, is a history of repeated migrations of diverse floristic elements, arriving in the region from various directions, persisting there for various lengths of time, and finally retreating under the pressure of environmental changes which made their position no longer tenable. This history has been complicated by the extinction of old and the differentiation of new species, by the mingling of species of originally different history, and by the persistence of isolated relics of early migrations. In all these respects, vegetational history exhibits a striking parallelism to human history. Thus Europe has witnessed during the last two millenniums the extinction or absorption of the early Iberians, the persistence of the Basques, the arrival and retreat of the Moors and Turks, and an enormous evolution in culture. Furthermore, the underlying causes of vegetational and human history are similar, even though the human species exhibits an exceedingly complex relation to its environment. The geography of man has long been recognized as merely the present condition of his history, and the relations of both to natural conditions and processes have been well summarized.[7] Unfortunately, no such summary exists for plants.

Outline.—It has therefore been necessary to preface this history of plant life in the Middle West, presented in Part IV., by a discussion of the conditions and nature of plant migrations in Part II., and by a resumé of the evidence used in determining past migrations in Part III.

Part II. The General Nature of Plant Migrations

A great body of literature dealing with the migration of plants has appeared in the last century and a half. This has been so well summarized by Clements[8] that it needs no further discussion here. Most

[7] Semple, Ellen C. Influences of geographic environment. New York, 1911.

[8] Clements, Frederic E. The development and structure of vegetation. Studies in the vegetation of the state III. Botanical Survey of Nebraska VII. Lincoln, 1904.

of it deals with the migration of individual species, and Clements' exposition of the whole subject is without doubt the best general treatment extant.

Invasion, Migration, Ecesis.—Following Goeze, he considers the general movement of species or associations under the term *invasion,* and recognizes that this consists of two distinct processes. One of these, to which he restricts the term *migration,* involves merely the movement of the plant by means of its reproductive bodies or vegetative processes. The mechanics of such movement, the methods of seed dispersal or vegetative propagation, while exceedingly diverse, are already well understood and require no discussion here. The second process, which he terms *ecesis,* includes the actual establishment of the plant in a new location. Ecesis depends entirely upon the environmental conditions of the new location in their relation to the physiological requirements of the seedlings. The details of these relations are for most plants entirely and for all plants mostly unknown, and are to be determined by the methods of experimental ecology. Migration, in Clements' use of the term, is completely unsuccessful in the failure of ecesis, and ecesis, to be effective and complete the process of invasion, must be carried to the maturity of the plant and the production of a second generation of disseminules. The distinction between the two processes is fundamental, and Clements' clear analysis has done much to systematize the knowledge of the subject.

The term *invasion,* which Clements applies to the whole phenomenon of movement, is in many cases scarcely appropriate. His own definition and the general meaning of the word both imply a movement of plants into an area not before occupied by them, that is, an extension of their range. As a matter of fact, the migration of plants is almost or quite as frequently out of an area previously occupied as into a new one, and then involves a retreat or restriction of their range, a result to which the term invasion can not be properly applied. The term migration, in the sense of Clements, is distinctly a process of one generation. Ecesis involves the development of a second generation of individuals, but scarcely applies to the whole population of a species. Yet these processes, participated in by a whole population and continued regularly through successive generations, may lead to broad results far more inclusive than those chiefly considered by Clements. For the purposes of this article, the migration of plants is understood as any general movement by which the range of a species is changed.

Efficiency of Plant Dispersal.—The efficiency of plant dispersal is well understood. Each normal individual produces one or many

crops of seeds or other reproductive bodies and these are dispersed thoroughly over the surrounding territory to an extent dependent upon their structure and their environment. At the margin of the present range of a species, whether that margin is the boundary of an association in which it occurs or the general margin of its whole range, seeds are annually dispersed in all directions, inward through its present range and outward and beyond it as well. Examples of this are well known and need not be cited. Except in comparatively infrequent cases, where the ability to produce seeds or other reproductive bodies is lost, the potentiality of continuous and extensive migration is constantly present. The slow rate of actual normal migration is not due to inefficiency of the migratory devices of the plant, nor, except as mentioned above, to deficient seed production, but to the inhibiting effect of environmental factors in the area beyond the present distribution of the species. This is particularly true toward the center of the range. Every swamp is annually and abundantly planted with seeds of upland species, while the swamp plants are simultaneously distributed over the upland, and in neither case do any of them grow, except under the most unusual circumstances.[9] Even at the margin of the specific range, where reduced or intermittent seed production might be expected, Griggs has shown that many species are able to propagate themselves freely.[10]

There is for each species a general limit of distance over which its seeds may be dispersed. The number of seeds arriving on any area diminishes with increasing distance from the parent plant; in fact, for small distances, the number seems to vary inversely as the square of the distance. Since only a small portion of the seeds germinate and grow to maturity, most young plants of the second generation are located relatively close to the parent.

Migration and Succession.—Actual migration, therefore, requires a change in the existing environment for its inception. (The abnormal type of migration, due to the acquisition of new means of dispersal by which previous environmental barriers are crossed, is mentioned in a later paragraph.) A migratory advance postulates the development of individuals in territory not previously occupied and requires an environmental change of sufficient extent not merely to permit the growth of the migrants, but to permit it against the competition of the previous inhabitants. A migratory retreat requires a detrimental

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[9] Brewster, William. Occurrence of the skunk cabbage in an unusual place. Rhodora 11: 63, 64. 1909.

[10] Griggs, Robert F. Observations on the behavior of some species at the edges of their ranges. Bull. Torrey Club 41: 25–49. 1914.

change, either in physical conditions or in their control by plant life or in parasites and enemies, sufficient to prevent the establishment of new plants in the immediate vicinity of the parent, so that the species disappears from the habitat with the death of existing individuals. Succession results when migration is so complete and is shared by individuals of so many species that the nature of the vegetation is fundamentally changed. The close relation between succession and migration have been noted elsewhere,[11] and the nature of the causal environmental changes have been discussed in detail by Clements.[12] Instances are of course well known in which species migrate into an association and become an integral part of it without causing succession. Thus in parts of New Jersey *Daucus Carota* has entered the hemlock-maple forest, and in northern Michigan *Rumex Acetosella* has become widely distributed through the aspen association. Such a result may be termed taxonomic succession, as distinguished from the ecologic succession previously mentioned.

Rate of Migration.—The simple production, movement, and establishment of reproductive bodies, constituting together the method of migration, is not the only factor concerned in the process. The rate of migration depends upon one or the other of two conditions: the rate of environmental change and the migration-capacity of the plant. The latter condition may in turn be resolved into two components; the mobility of the plant, depending on the structure of its migrating parts and its ability to utilize the necessary environmental agencies, and the length of its juvenile period, which must be completed before a new crop of disseminules is produced to continue the march. Migration-capacity may be formulated in general terms as mobility divided by length of juvenile period. Hence those plants which combine excellent structural devices for dispersal with a short vegetative cycle, such as the dandelion (*Taraxacum*), migrate more rapidly than others with less mobility, as lamb's-quarters (*Chenopodium*), or with a long vegetative period, as the maple (*Acer*), while slowest of all are those plants which lack both favoring features, as the oak (*Quercus*). The actual rate of migration is fixed by the slowest of the two general conditions. If environmental change is slow, migrating species may keep even with it and continually scatter their seeds forward into territory where they can not yet grow. If environmental change is rapid, the slower species may not be able to keep even with it and consequently follow

[11] Gleason, H. A. The structure and development of the plant association. Bull. Torrey Club 44: 463–481. 1917.

[12] Clements, Frederic E. Plant succession, an analysis of the development of vegetation. Carnegie Inst. Washington, Publ. 242. 1916.

at a distance far behind other more mobile forms. Thus in the slow extinction of a pond by the deposition of peat, there is no break in the time-continuity of the contracting zones of vegetation around it, since mobility exceeds the rate of environmental change. But if a pond is drained artificially, producing in a single year an effect similar to that of a century of peat formation, the more mobile species enter first on the freshly exposed area and some years may elapse before all the remainder have appeared. So also the sudden cessation of prairie fires on parts of the prairies led to the immediate advance of the forest, and the more mobile species composed the bulk of the early invaders. In general, migration connected with physiographic succession keeps pace with the environmental changes, so that associations are well marked and the correlation between zonation and succession is prominent. Even such a slow environmental change as the advance or retreat of a continental glacier may have been too rapid for some species, while certainly slow enough for others. Numerous species were doubtless destroyed completely with the advance of the glaciers and others during their retreat, from inability to keep pace in their migration with the changing conditions of the environment.

The most rapid rate of migration is found in the anthropochorous species which utilize human activities for their dispersal. Such not only move with extreme rapidity, but by the nature of their dispersal are able to cross barriers quite impassable for other species. Our own country has been occupied during the past century by hundreds of such species which have crossed an ocean to reach us and have spread hundreds of miles over the land in a very short time. Yet most of these same species are stopped completely by an area of undisturbed natural vegetation, which they are unable to colonize.[13]

THE TIME FACTOR AND MIGRATION.—The present status of migration depends upon its rate, as discussed in the preceding paragraph, and on the elapsed time since migration began. The more rapidly moving species may be at the limit of their present potential range and wait upon further environmental change, while the slower ones may be far from their actual limit, although progressing toward it at their best speed. The condition is well illustrated in the belts of forest which parallel the rivers of Kansas and Nebraska, in which, in general, the more mobile species have extended farthest to the west.[14] It is also prominent throughout the prairie region of the Middle West, where

[13] Gleason, H. A. & F. T. McFarland. The introduced vegetation of the vicinity of Douglas Lake, Michigan. Bull. Torrey Club 41: 511–521. 1914.

[14] Kellogg, R. S. Forest belts of western Kansas and Nebraska. U. S. Dep. Agr. Forest Bull. No. 66. 1905.

there is a continuous movement of the more mobile forest species into the land originally occupied by prairies.

The time factor naturally begins with the origin of the species concerned. Those of relatively recent origin have had little time in which either to extend or to contract their original ranges. Since major environmental changes are usually slow in their accomplishment, recent species have in general had also relatively little opportunity to use their migratory abilities. Such species are therefore restricted more closely to the site of their origin.

It is probably true, however, that many of our species have not had a single point or even a limited area of origin. The bulk of later Tertiary plants, as far as palaeontological evidence indicates, are of genera still existing, and many of the comparatively few known species of Pleistocene plants are either identical with or closely similar to existing species. Such evidence deals especially with woody plants, but what is true of them is doubtless true of herbaceous plants as well. The distinction between such Pleistocene plants and their modern representatives may depend largely on a break in the record, on a period from which fossils are lacking. Probably if a complete series of specimens were at hand, showing comprehensively the maples of the eastern states, for example, from the Pliocene to the present time, it would be seen that some of the earlier forms are absolutely continuous with our present species and that the slight morphological distinctions between them are only the result of continuous slow variation throughout the centuries. According to this view, many modern species had no localized origin and are not the offshoot of any parent, but represent the mass development of a species, which, under our present taxonomic ideas, came to a stop at the beginning of a break in our geological record of it and reappeared as a new species at the beginning of our next experience with it. During the long history of such a species, most of which is unknown to us, it may have migrated repeatedly in various directions, occupied larger or smaller areas, been separated into disjunct regions and again united, or one part of its population exterminated, and its range as we see it today represents merely the present condition of this long development. We are never sure of the prehistoric stages in this history, through the imperfections in the fossil record, but in certain cases we can arrive at some idea about them by circumstantial evidence.

Such a consideration does not account for the multiplication of species. Whether that is caused by mutation, natural selection, or hybridization, it seems certain that their perpetuation to the present time has depended greatly upon their ability to migrate as changes of environment demanded.

Significance of the Margin of Range.—The margin of the range of a species, then, does not always represent the boundary of the territory in which the species can or will live under present conditions, but merely the distance which it has travelled so far in its march to this goal. Instances are not lacking, of course, in which this migration has been completed and further extensions or retractions of the range wait upon future climatic changes. As one illustration, the distribution of *Pinus ponderosa* along the eastern foothills of the Rocky Mountains may be cited, where it has been clearly shown[15] that the species is now at the margin of its potential range. On a smaller scale, a sharply marked boundary between two associations indicates completed migration in that restricted area of the species on both sides of the boundary to the limits permitted by the present environment.

Advancing and Retreating Migrations in the Middle West.—Both advancing and retreating migrations are now in progress in the states of the Middle West. In most cases these movements are too slow to come under direct observation, and reported extensions of ranges are generally due to incomplete or faulty early observations. Still the rapid spread northward of *Prosopis glandulosa* from Texas across Oklahoma into Kansas,[16] the westward migration of trees along the rivers of Nebraska,[14,17] and the recent discovery of young trees of *Quercus palustris* in southeastern Nebraska[18] may be cited as instances of visible migration. In general, migration is shown chiefly by the rôle of the species in succession. If, at or near the edge of its range, it participates in succession as an invading species, it is advancing; if it is not able to hold its own in competition, if the associations of which it is a member are regularly succeeded by others of which it is not a part, a retreating migration is indicated. This is illustrated in Michigan and Wisconsin by the regular succession of coniferous associations by deciduous forests, indicating the retreat of the conifers and the advance of the deciduous trees.[19]

Effects of Changes in Physiological Requirements.—There is no reason why changes in the physiological requirements of a species

15 Dodds, Gideon S., Francis Ramaley, & W. W. Robbins. Studies in mesa and foothill vegetation, I. Univ. Colorado Studies 6: no. 1, 11–49. 1908.

16 Bray, William L. Distribution and adaptation of the vegetation of Texas. Bull. Univ. Texas 82. 1906.

17 Bessey, C. E. Are the trees advancing or retreating upon the Nebraska plains? Science II., 10: 768-770. 1899.

18 Pool, Raymond J. Pin oak in Nebraska. Torreya 20: 50-52, 1920.

19 Whitford, H. N. The genetic development of the forests of northern Michigan: a study in physiographic ecology. Bot. Gaz. 31: 289–325. 1901.

might not have the same effect as a change of environment in causing migration. It is well known that plant breeders have developed new races of cultivated plants which thrive in climates different from that of the original home of the species. Possibly the rapid spread of American Opuntias in parts of Australia may be explained in this way. Under natural conditions, such changes in physiological requirements are usually correlated with changes in structure, and the latter are used as a basis for taxonomic differentiation. Whenever such evolutionary changes appear, new areas may be opened to the new species and eventually occupied by them. So such genera as *Eupatorium* and *Vernonia,* originating probably in northern South America, have migrated northward into the cold-temperate zone, as evolution has changed their physiological requirements and morphological structure. So have bromeliads migrated away from the humid tropical forests, entered the deserts of southern Mexico, and established themselves as epiphytes on the cacti;[20] so have the cacti migrated out of the desert region, where they probably originated, and established themselves as epiphytes in the tropical forest.

Migrations as Related to Continuity of Suitable Habitats.—The range of every species is discontinuous. Throughout its whole area only particular habitats are occupied, leaving others to different species and associations. In each habitat, the space is shared with other associated species. These phenomena are in general of ecological rather than geographical interest, but are still of importance in their relation to the direction of migration. Within the habitat, so far as the association is continuous, even the least mobile species may migrate freely and ultimately attain a uniform distribution.[11] But from one habitat to another, the means of dispersal must be sufficient to carry the species across the intervening gap, which becomes a barrier to the less mobile forms. During the long course of time, accidents of dispersal may carry many species across a barrier, but accidents are probably not as efficient as frequently supposed. Mink Grove and Lynn Grove, two isolated areas of forest in Champaign County, Illinois, had large trees in them when first observed by white men nearly a century ago, and their age is doubtless 150 years at a minimum. Although these groves lie but a few miles from the nearest strips of forest along streams, in which species of *Hicoria* and *Quercus* are abundant, not an individual of these genera has reached them. Extensive migrations of plants, proceeding at a relatively rapid rate, therefore take

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[20] MacDougal, D. T. Botanical features of North American deserts. Carnegie Inst. Washington, Publ. 99. 1908.

place along routes where suitable habitats are nearly continuous, such as river valleys for mesophytic species or interfluvial uplands for xerophytic forms. There is every reason to believe that the post-glacial migration of the deciduous forests into the Middle West followed the river courses almost exclusively. From these earlier migrations along the line of least resistance, a slower type of migration gradually extends the range out upon other habitats. This follows regularly the physiographic development of an area, as Cowles has shown,[21] and may also be induced by the reaction of an association upon the environment in the margin of a contiguous association beyond it.[11] So the forests of the Middle West, entering the region along the nearly continuous habitats of the river courses, where they migrate rapidly, have also spread at right angles to them, but more slowly, until in some cases those of different river systems have become united.

Each important change in the climate or the configuration of the land, due to geological causes, has created new migration routes and destroyed old ones, interrupting migrations then in process and initiating new ones, which may progress in different directions and be participated in by plants of different origin. There is evidence of several such migrations in the Middle West, which are discussed in Part IV.

THE INTERPRETATION OF ISOLATION.—Actual geographical isolation of a species, in the ordinary sense, is effective only when an outlying habitat is separated from the general range by a distance greater than the migration-capacity of the plant. Instances of this are too well known to need citation. Only two explanations are possible for such a condition. Either the species has had two separate and independent origins, or else the vicissitudes of migration have brought it about. Even if the possibility of the former alternative is admitted, the latter is the more plausible in the majority of cases. It implies that the two disjunct bodies of the species were at some time one, either in a territory from which both portions have migrated and which is no longer occupied, or through the existence of connecting links between the two which have now disappeared. Both cases have been caused by a retreating migration.

Environmental changes which permit the advance or compel the retreat of one species are quite likely to affect others similarly, since associated species demand in general the same environment. Migration is therefore concerned with numerous species simultaneously.

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[21] Cowles, H. C. The physiographic ecology of Chicago and vicinity; a study of the origin, development, and classification of plant societies. Bot. Gaz. 31: 73–108, 145–182. 1901.

Whole floras migrate together, the hardiest and most mobile species first, the others in their train. They establish successional series in the region which they enter, and build up new associations in the new territory. These are analogous to the associations of their original range, but differ in the absence of the slower moving species and in the presence of laggards from the retreating flora.

Just as portions of a single species may be isolated during its migrations, so may areas of one type of vegetation be completely surrounded by an advancing flora and left isolated from the main body. These are known as relic colonies. The cause of such isolation is the failure, up to the present time, of sufficient environmental change to cause their extinction, or, in ecological terms, it is the relative slowness of the succession in certain habitats unfavorable to most of the advancing species. These habitats remain with their original vegetation upon them, while elsewhere it is displaced. Such relic colonies are of common occurrence wherever migrations are recent. Every movement of vegetation has certainly left relic colonies behind it, but their perpetuation to the present time depends absolutely on the continuation of an environment not only favorable to the relic species but distinctly unfavorable to the invaders.

Adjustments in Distribution.—The distribution of a species and the distribution of vegetation must both be regarded as subject to continual adjustment. Boundaries extend and contract, associations advance and retreat with every geographical fluctuation of the environment. Even within the limit of a single association, every minor environmental variation, whether geographical or seasonal, is marked by the entrance or disappearance of some species, or by changes in the numerical proportion of the others. This may account for the conditions recently reported on Mt. Marcy,[22] where twenty-one species formerly reported by Peck have apparently disappeared and seven " rather conspicuous plants, which such a careful botanist could scarcely have missed, have apparently come into the flora."

General Results of Continued Migrations.—Obviously the general result of continued migrations is the mingling of floras of diverse origin, while great climatic changes or important geological episodes tend toward the segregation of floras and the consequent initiation of new migrations. Regions affected by Pleistocene glacia-

[22] Adams, C. C., Geo. P. Burns, T. L. Hankinson, Barrington Moore, & Norman Taylor. Plants and animals of Mount Marcy, New York. Ecology 1: 71-94, 204-233, 274-288. 1920.

tion, such as the area here discussed, fall in this group, and in them floras of different origin are still relatively distinct and adjustments of range are actively in progress. On the other hand, in regions which have enjoyed relatively uniform environmental conditions for a long period of time, migrations are more generally completed and vegetation is in more nearly a static condition, except in those successional series which are related to continuous physiographic processes such as baseleveling. This is now the case in parts of the tropics, and was formerly the case over wide areas of the North Temperate zone in the later Cretaceous and earlier Tertiary periods, when the flora and vegetation of North America and Eurasia were remarkably uniform.

Summary of Part II.—1. Migration of a species depends on an environmental change within or beyond its range.

2. The rate of migration depends on the rate of environmental change or the migration-capacity of the plant.

3. The present status of migration, as shown by the range of the species, depends on its rate and on the time available for it.

4. The present range of a species is not necessarily final, even without further environmental change.

5. Migration proceeds most rapidly along routes with nearly continuous habitats.

6. Species of similar environmental demands migrate together.

7. Isolated areas of a species or of vegetation are to be interpreted as results of retreating migration.

8. Long continued uniformity of environment leads to floristic uniformity; recent environmental changes to floristic segregation and to new migrations.

Part III. The Evidence of Plant Migrations

The entire distance which may have been travelled by the native plants of the Middle West in their migrations since the close of the last glaciation seldom exceeds 500 miles. Since the time available for this movement may be 10,000 to 40,000 years, this requires an average annual migration of only 66 to 264 feet. In the case of trees, a juvenile period of 20 years would still necessitate a movement during one generation of not more than a mile. The discovery of migrations still in progress is accordingly removed from direct observation, except in the case of a few species, and any conclusions must depend entirely upon historical or indirect evidence.

Historical Evidence of Migrations.—Historical evidence may occasionally be used with considerable success, especially where civilization has existed for a long period of time and written records preserve trustworthy accounts of some of the original features of the vegetation. Thus Graebner[23] has been able to demonstrate that certain heaths of northern Germany were originally beech forests. Tansley[24] has also made frequent use of historical records. For the Middle West, such data cover little more than a single century and are correspondingly restricted in value. There are, however, numerous early books of travel which give fairly accurate accounts of the plant life. Their descriptions of prairie fires, of the former extent of prairies, and of the oak openings are in many cases excellent and may probably be relied upon completely. They generally lack detail and seldom mention many species by name, but are nevertheless better for phytogeographical purposes than the floras compiled by early botanists. In almost every county seat copies of the original land survey maps may be consulted. On many of them various features of the vegetation are shown, such as the occurrence of swamps, prairies, and barrens. In some cases the nature of the forest may be approximated by reference to the accompanying field books, since the surveyors' monuments were usually located with relation to certain described trees.

Succession as Evidence of Migration.—For migrations still in progress, the most valuable line of contemporary evidence is found in the successional relations of the species toward the margin of their ranges. Even there, succession can not generally be observed directly, but numerous other considerations offer convincing evidence of the nature of the process, such as the relation of the associations to physiographic development, the reaction of the plant cover on the environment, the presence and relative abundance of seedlings, or the relative age of individuals. These have been used so freely by ecologists and such a body of accepted data has been published that they need no discussion here. Nevertheless, a timely warning against the too general application of the principles of succession has been sounded by Harvey[25] and deserves careful consideration. When, at or near the margin of a range, a species or the members of a flora of uniform geographical distribution participates in successions as invading species, they are

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23 Graebner, P. Die Heide Norddeutschlands und die sich anschliessenden Formationen in biogischer Betrachtung. Die Vegetation der Erde, vol. 5, Leipzig, 1901.

24 Tansley, A. G. Types of British vegetation. Cambridge, 1911.

25 Harvey, Leroy H. Some phytogeographical observations in Lake County, Michigan. Mich. Acad. Sci. Rep. 21: 213–217. 1920.

extending their range. Similar behavior toward the center of the range may indicate only a general closing-up process, representing the later slower stages of a migration and not implying any general extension of range in the ordinary sense of the word.

The known successional tendencies of the three major types of vegetation of the Middle West have frequently been described, especially the tendency of the deciduous forests to succeed the prairies toward the west and the coniferous forests toward the north. Project this tendency into the future and it points to a still wider extension of this type of forest, with a corresponding restriction of prairie and coniferous forest. Project it into the past and it reveals a former condition of restricted deciduous forest and of a larger extent of prairie and coniferous forest. Obviously, such reasoning must not be carried too far, and its results must always be checked by the existence of relic species or relic colonies, as discussed in a following paragraph.

The stratigraphic sequence of fossils has been used with great success as one line of evidence in Europe.[26] While similar evidence has already yielded important results in America, the necessary data for extensive generalizations are usually lacking or deficient. The careful examination of the structure of peat has scarcely more than begun in this country, and the pioneer work of Dachnowski[27] may lead to important results.

Geological events must have necessitated certain migrations and by their very nature give a general idea of them. Thus it is incredible that beech-maple forests could have occupied northern Michigan during the maximum advance of the Wisconsin glaciers, which reached some 400 miles farther south. A northward movement of these trees and their associated species to their present location must have taken place after the retreat of the ice, but the details of this migration must be discovered by other lines of evidence.

Determining Migration Centers.—Adams[5] has advanced certain criteria for determining the migration-center of animals, which are in many cases equally applicable to plants. They are, with two omissions, as follows:

1. Location of greatest differentiation of a type.
2. Location of dominance or great abundance of individuals.
3. Location of synthetic or closely related forms.

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[26] Lewis, F. J. The plant remains in the Scottish peat mosses. Part I. The Scottish southern uplands. Trans. Roy. Soc. Edinburgh 41: part 3, 699-723. 1905.

[27] Dachnowski, Alfred P. Peat deposits and their evidence of climatic changes. Bot. Gaz. 72: 57-89. 1921.

4. Location of maximum size of individuals.
5. Continuity and convergence of lines of dispersal.
6. Location of least dependence on a restricted habitat.
7. Continuity and direction of individual variations or modifications radiating from the center of origin along the highways of dispersal.
8. Direction indicated by biogeographical affinities.

The Five Elements in the Flora of the Middle West.—Applying his principles to the vegetation of the Middle West, it is found to be composed of five elements, not of equal importance, centering respectively in the southern Appalachian Mountains, in the southern Coastal Plain and the Mississippi Embayment, in the Ozark Mountains, in the plains of Kansas and Nebraska, and in Canada east of the Great Lakes. Four of these lie beyond the glaciated region far enough to have suffered little or not at all from the advance of the ice, and there is no reason to believe that they did not occupy these positions continuously through the later glacial period. The last one is in the glaciated region, and must have been developed since the retreat of the ice from a temporary refuge farther south. For the first four, we are probably safe in assuming that all subsequent migrations of their floral elements have been on lines essentially radial, either from or toward these centers, as ranges may have extended or retreated. For the fifth, we are undoubtedly correct in assuming a general northward shift of the whole flora following the ice retreat.

Glacial vs. Modern Climate.—The close similarity between the interglacial and the modern floras, so far as evidence is at hand, indicates that the glacial climate differed from the modern not so much in kind as in degree. It may be expected accordingly that migrations of the deciduous forests took place first in a northward direction from their Appalachian center and later westward into the Middle West, and that any eastward migration of a prairie flora took place toward the north of our area, where there is still a marked distinction between winter and summer rainfall and a generally smaller total amount, rather than at the south where rainfall is more abundant and more evenly distributed throughout the year.

Further evidence may be drawn from the topography of the region. Large and sharply marked moraines may indicate a rapid advance of the glacial ice. Wide stream valleys leading from the moraines, with great outwash deposits, may indicate rapid melting of the ice under relatively high temperatures, and consequently in the adjacent region a flora and vegetation correlated with such climate. Such evidence has been used chiefly in connection with the Wisconsin glaciation, where

it seems that the temperature at the time of maximum ice advance was high and probably not unlike that of the present time. The immature development of the drainage systems over the Wisconsin drift, particularly toward the west, may also be due not merely to youth but also to an early postglacial climate drier than that of the present day.

If a considerable number of species are now confined to an area immediately beyond a moraine and seldom or never occur within it, their distribution may be explained in several ways. First and most obviously, present conditions of soil and climate may exclude them. But if the general vegetation and climate of the two regions are similar and if habitats apparently identical, as judged by the vegetation, exist on both sides of the moraine, this explanation is less plausible. Secondly, their migration up to the present time may have extended merely to the moraine, which they will later cross. But it is difficult to understand why the boundary of the range of numerous species should be so nicely adjusted to the moraine. The third explanation, which is here accepted, is that they occupied this area before or during the formation of the moraine, have occupied it ever since, and are not at present extending their range.

Relic Colonies.—Lastly, and most important of all, past migrations may be judged by relic colonies. Unfortunately, they can be used only for the more recent movements, since the relics of earlier migrations have been completely destroyed. Many such colonies still exist, isolated by recent migrations, or did exist long enough to be recorded before being sacrificed to agriculture, and afford the most valuable evidence of the past range of the floras which they represent. They even give valuable clues to migrations of still earlier date, during which the flora of the colonies entered the region, and therefore show at once an early advance followed by a later retreat.

Although the probability of extreme migrations, except in the case of very mobile species, is very slight, the time available is very long and has certainly been sufficient for the improbable to happen many times. Therefore, in general, isolated stations of a single mobile species shed little light on its past history. But isolated colonies of several or many species, provided with diverse methods of dispersal, represent a different condition. It is entirely beyond the limits of probability or coincidence to presume that a dozen or more species, normally growing together in one section of the country, should also be found together in another remote section beyond the normal limits of dispersal of any of them. Isolated colonies of this character are common phenomena in the Middle West and can have but one significance, that at some time in the past these colonies were more numerous and separated by narrow

intervals within the normal migration-capacity of the species, or were entirely continuous over the whole area. Stated in more general terms, the present occurrence of relic colonies indicates the past extent of the vegetation of which they are a type. For the same reason, isolated stations of a single relatively immobile species indicate a former more nearly continuous distribution, and evidence from this source is of greater importance when the species in question is regularly associated with some peculiar or unusual habitat.

A combination of evidence from successional tendencies and relic colonies indicates both the direction and the extent of prehistoric migrations. The full extent may not be indicated, because the isolated colonies may have disappeared completely from the more remote parts of their original range. In such cases isolated stations of single species may give some not entirely untrustworthy idea of it. The farther back in time plant migrations are traced, the fewer relic colonies may be expected and the more dependence must be placed on individual species.

No one of these various lines of evidence is sufficient in itself to build up a history of vegetational movements in the Middle West. All of them must be used together and the deductions from all woven into a history which accounts for present conditions satisfactorily and is plausible in itself. The development of this history must be commenced with the present, where the latest migrations are shown by successional relations. The extent of these recent events may be estimated and checked by relic colonies, which in turn point to earlier migrations. These must be checked by glacial topography, by inferences concerning glacial climates, and by the distribution of plants along the moraines. Still farther back, plant distribution and migrations must be deduced from fossils, from the location of the moraines, from the known physiological requirements of the plants, and through the use of Adams' criteria.

The vegetational history which follows in Part IV has been constructed in this way. Observed conditions and recorded vegetational changes during the historical period have given evidence on migrations then in progress and permitted deductions as to those of the later prehistoric period. Conclusions as to the preceding stages have been reached through use of the various lines of evidence outlined above and carried back with decreasing detail and assurance to the advance of the Illinoian glaciers.

Summary of Part III.—1. Migrations in progress now or in the recent past are indicated by historical evidence or by observation of successions.

2. Former migrations are indicated by the occurrence and distribution of relic colonies and species, by ecological and taxonomic evidence as stated by Adams, by glacial history and topography, by fossils, and by inferences as to former climate.

3. Evidence from all available sources must be combined to build a plausible and possible chain of events, leading on to and culminating in the known present distribution of plants.

4. Conclusions as to early stages of plant distribution and migration are reached in reverse order of their occurrence, that is, from present to past. The accuracy of each conclusion depends on the accuracy with which the conditions of the following stage have been interpreted. Each earlier stage must therefore be discussed in less detail and with greater probability of error.

PART IV. THE DEVELOPMENT AND HISTORY OF VEGETATION IN THE MIDDLE WEST

PREGLACIAL.—From the close of the Carboniferous Period to the Lower Cretaceous or Comanchean Period, the area now comprised between the Missouri Valley and the Appalachian Mountain system was continuously land. The pteridophytic and gymnospermous flora which occupied it can be partly reconstructed from the fossils of those ages, but its migrations are unknown. During the Lower Cretaceous the first representatives of the angiosperms must have arrived in our area, since the fossil remains of such plants are preserved in contemporary deposits still farther west, and through the Upper Cretaceous angiosperms constituted the dominant vegetation. It is not probable that herbs were prominently developed; angiosperms consisted chiefly of woody plants of families and genera still in existence in the area and of other groups now primarily or exclusively tropical. This flora is undoubtedly continuous with the forest flora of the Tertiary, usually designated the arctotertiary flora, and through it with the forests of the present.

While there may have been differentiation of floristic types in the Cretaceous, correlated with local climatic conditions, the first of the great vegetational segregations which is still of importance in our region began at the close of the Cretaceous with the uplift of the Cordilleran complex of mountains.[28] Intercepting the moisture-laden winds from the Pacific and restricting the rainfall of the lands immediately east of them to moisture derived from the Gulf of Mexico, the elevation of these mountains led to the development of semiarid conditions over the Great Plains, which soon had an effect on the

[28] Harvey, Leroy H., Floral succession in the prairie-grass formation in southeastern South Dakota. Bot. Gaz. 46: 81-108. 1908.

character of the vegetation. The result was the grassland type which still prevails in that region.

This result naturally required thousands of years for its accomplishment, but the *modus operandi* may be summarized as involving five processes: (1) the disappearance of the arborescent flora; (2) the great increase in the number of individuals of the herbaceous species; (3) competition for space among the herbs, leading to the eventual dominance of the grasses, as the group best suited by growth-form and ecological requirements to the new conditions; (4) the development by evolution of new and characteristic species and genera, and (5) the immigration, usually accompanied by specific or generic evolution, of other species from the Sonoran deserts at the south and the Great Basin deserts at the west.

How far toward the east the prairie vegetation may have extended in Tertiary time and how many advances and retreats it may have made in response to climatic variation are unknown. We may believe, however, that the present climatic center of the Prairie Province in western Kansas and Nebraska and eastern Colorado has been occupied by this vegetation continually since its origin, and that amoeba-like arms have been pushed out many times in many directions and withdrawn again. It is also probable that the arctotertiary forests have continuously occupied the Ozark uplift, since it still harbors many old species, although not so many as the Appalachian uplift of the same latitude, from which it was isolated during the Tertiary by the oceanic waters of the Mississippi Embayment. This isolation and the proximity of the Ozarkian region to prairie and Sonoran floras on the west have led to a considerable differentiation between the Ozarkian and Appalachian forest centers, as has already been noted in Part III.

Fossil evidence indicates that the arctotertiary flora included both angiosperms and gymnosperms and had little or no latitudinal differentiation, at least as far north as 70°. The second great floristic development affecting our region was the general segregation of these two groups into a northern flora, with gymnosperms predominating, and a southern flora, in which angiosperms were dominant. This probably began only with the approach of the first glacial period and may not have been completed until the ice age was well under way. The processes were essentially the same as those outlined above for the prairie vegetation, but in this case involved also the permanent disappearance from both floras of a number of species belonging to genera whose modern representatives are tropical. The former presence of *Ficus, Artocarpus, Sabal,* and other genera of similar climatic requirements in northern latitudes has frequently been taken to indicate a tropical or subtropical climate in those regions. The writer sees no

reason for believing that such genera could not have produced species adapted to a temperate climate then, just as *Phoradendron, Diospyros,* and *Tripsacum* have at present, so that the actual shift of climate northward may have been only a few hundred miles.

These three floristic and vegetational types have since maintained their identity, and the history of the vegetation of the Middle West is concerned almost exclusively with them. A fourth floristic element, the Coastal Plain flora of the southeastern states, was likewise segregated from the arctotertiary forests, probably during the late Tertiary or Pleistocene, and enters the southern portion of our region, but has probably never occupied a more extensive territory than at present. The Coastal Plain flora has been considerably modified by the immigration, accompanied by evolution, of numerous tropical forms, entering the region via Texas or the Florida peninsula. Some of these have extended still farther north and have invaded other floras as well.

Early Glacial Stages.—There is no present evidence concerning the migrations of vegetation during the Nebraskan and Kansan glacial advances, at least one of which entered our area, or during the corresponding Aftonian and Yarmouth interglacial stages, and the earliest evidence at hand deals with its location during the Illinoian period at the time of maximum advance of the ice.

The southern boundary of Illinoian glaciation extends in a generally southwesterly direction across Ohio and Indiana and lies on the northern slope of the Ozark uplift in southern Illinois. It then turns northward, following in a general way the present course of the Mississippi river to the Wisconsin border, displacing the river westward in eastern Iowa, but passing to the east of the driftless area in northwestern Illinois. Its deposits in Wisconsin are almost wholly covered by those of a later period and its further extent in the Middle West is unknown.

The pre-Illinoian flora of the territory covered by this ice sheet must have been destroyed or have migrated south, west, or in both directions. The immediate problems are to ascertain the distance beyond the glacial boundary to which it was forced and the location of the extraglacial floras during the time of maximum ice advance. Several features of present distribution seem to cast some light on the questions.

The Mississippi Embayment.—The Mississippi embayment of southern Indiana, Illinois, and Missouri is occupied by a large number of species which reach here their northern limits in the extensive floodplains of the Ohio, Wabash, and Mississippi rivers, without migrating farther to the north along these floodplains into glaciated territory.

Noteworthy among them are *Taxodium distichum*,* *Rhamnus caroliniana, Gleditsia aquatica, Nyssa aquatica, Ilex decidua, Catalpa speciosa, Fraxinus profunda, Celtis mississippiensis, Quercus Phellos, Leitneria floridana,* and a host of other shrubs and herbaceous species. Soil conditions can not be cited as the cause of this range, because the soils in which these plants grow is all alluvial, washed down by the streams from the glaciated region, and parallels them without any essential difference for miles within the glacial boundary. Neither can climate be cited, since two of them, *Taxodium distichum* and *Catalpa speciosa,* are commonly, and others occasionally, cultivated 200 to 300 miles north of their natural limits.

Northern Limits of Southern Plants.—The rocky hills of the Ozark uplift in southern Illinois also carry a number of southern plants which reach here their northern limits, such as *Pinus echinata, Batodendron arboreum, Ulmus alata, Azalea nudiflora, Bumelia lycioides, B. lanuginosa,* and many others. These also have failed to utilize the extensive strip of similar habitats along the rocky bluffs of the Mississippi river for further migrations into the glaciated region. Still other species have interesting ranges correlated in some way with the glacial boundary. Thus *Heuchera parviflora* occupies isolated areas along the boundary only, with the exception of its stations in the lower Allegheny mountains. *Trichomanes Boschianum* preserves an outpost in southern Illinois, where it has recently been discovered by Cowles. *Sullivantia Sullivantii* occurs only along the glacial boundary from Ohio to Illinois and reappears in the driftless area 300 miles to the north. *Saxifraga Forbesii* is strictly limited to two stations along the glacial boundary in southern Illinois and southeastern Missouri. *Phlox Stellaria* is chiefly confined to certain limestone cliffs along the glacial boundary in Illinois and not far beyond it in Kentucky.

Undoubtedly there are species which reach their northern limit near the glacial boundary because of climatic conditions. This might be true of *Phoradendron flavescens,* whose host trees are abundant north of the boundary, but which has not crossed itself. But with numerous species with coincident range margins at this line, and several species with isolated stations near it, an easier explanation is that they remained here during the glacial period and have not migrated northward since then, indicating that the northern boundary of the arctotertiary forests lay parallel with and close to the ice margin.

There is at present no evidence whether this forest flora at that time extended westward toward the Ozarks, leaving northern Missouri

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* A single colony accurs in Knox County, Indiana, within the glaciated area.

and Iowa to a prairie flora of western affinity, or northward along the western boundary of the ice fields, restricting the prairie to a location farther west. Extensive forest beds overlie the Kansan drift in northeastern Iowa, as shown by McGee,[29] who states that more wood is preserved in these beds than at present grows in the area, but the time-position of these forests may be either Yarmouth, Illinoian, or Sangamon.

The Migration of the Conifers.—The conifers of the present northeastern forests, or their ancestral prototypes, migrated southward before the ice and must have been reduced to a narrow strip between the ice margin and the deciduous forests. There is no evidence whether this flora extended west as far as southern Illinois or existed in the unglaciated region of northwestern Illinois. It is noteworthy that *Pinus Strobus* does not occur on the exposures of St. Peter's sandstone near the confluence of the Mississippi and Illinois rivers, but its absence proves nothing. The only species of essentially boreal affinity now existing in southern Illinois are *Sullivantia Sullivantii* and *Saxifraga Forbesii,* and it is not necessary to presume that they were ever accompanied by coniferous forests. Such forests may have existed anywhere along the glacial margin, or may have been restricted to some especially favorable area, such as the re-entering angles in Ohio and Indiana, or to the mountains of Pennsylvania and adjacent states. The prominent development of vegetation of this affinity in the southern Allegheny mountains may have arisen during a later glacial advance or may have persisted since the Illinoian.

The Migration of Deciduous Forests.—During the long Sangamon interglacial stage which followed the retreat of the Illinoian glaciers, deciduous forests undoubtedly migrated to the north and probably also to the west. The full extent of this migration can at present only be surmised, since it must be ascertained wholly by fossil evidence, and this is in most cases lacking. Nevertheless, logs of both angiospermous and coniferous species are found frequently in the soil layer between the Illinoian drift and the superposed Wisconsin soil in various parts of Illinois. Leverett[30] has noted that the coniferous remains must not be considered evidence for the maintenance of such forests throughout the interglacial stage, since they probably were deposited at the end of it, just before the approach of another glacier. The notable discoveries in the vicinity of Toronto, summarized by Chamberlin and

[29] McGee, W. J. The pleistocene history of northeastern Iowa. U. S. Geol. Surv. Ann. Rep. II¹: 189-599. 1891.

[30] Leverett, Frank. The Illinois glacial lobe. U. S. Geo. Surv, Mon. 38. 1899.

Salisbury,[31] indicate that deciduous trees may have migrated during the Sangamon stage to distances some 500 miles beyond their present range.

There must have been other vegetational movements during the Iowan glaciation and the succeeding Peorian interglacial stage, but no evidence concerning them has been found, and none is expected from the region under discussion, except from fossils which may eventually be discovered in the Peorian soils. The Peorian stage may have had a relatively warm and arid climate, since during this time extensive deposits of loess were made over wide areas in the Middle West. This type of climate may have persisted into or even through the Wisconsin glaciation.

Wisconsin Glacial Period.—The close of the Peorian interglacial stage saw the advance of the Wisconsin glaciers, which as the last glacial invasion have left the greatest impress on the nature and location of the present vegetation. Originating in the Labradorian center, the ice sheet flowed in a southwesterly direction into our area, wholly covering the state of Michigan and partially covering Ohio, Indiana, Illinois, and Wisconsin. Toward the periphery, the ice sheet was divided into more or less well-marked lobes, with re-entering angles between them. The ice margin along the eastern boundary of Ohio reached nearly to the northern extremity of West Virginia, extended across Ohio in a generally southwesterly direction to a point not far north of Cincinnati, westward across Indiana in about latitude 39° 30′, westward into Illinois, and thence northward on about longitude 89° to latitude 45° in Wisconsin. Here the boundary again turned west, and another lobe extended south into the north-central portion of Iowa. Throughout this area there is an extensive development of moraines, the chronological relations of which have been discussed in admirable detail by Leverett[30,32,33] and Alden.[34] These moraines mark successive stages in the retreat of the ice, and it is to be hoped that the application of De Geer's methods to the region will eventually yield an approximate time-scale for their history, an event which will be of the highest importance in developing a clear idea of the consequent migrations of vegetation. At the same time, a continued study of the

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31 Chamberlin, T. C. & R. D. Salisbury. Geology. New York, 1907

32 Leverett, Frank. Glacial formations and drainage features of the Erie and Ohio basins. U. S. Geol. Surv. Mon. 41. 1902.

33 Leverett, Frank, & Frank B. Taylor. The pleistocene of Indiana and Michigan and the history of the Great Lakes. U. S. Geol. Surv. Mon. 53. 1915.

34 Alden, Wm. C. The quaternary geology of southeastern Wisconsin, with a chapter on the older rock formations. U. S. Geol. Surv. Prof. Paper 106. 1918.

peat deposits[27] is certain to yield precise information concerning the nature of the flora.

Outside the margin of the Wisconsin ice lay the five floristic groups of plants already mentioned, the prairie flora to the west, the Ozarkian forests to the southwest, the coastal plain flora of the Mississippi Embayment to the south, and the deciduous forests of the Appalachian and Piedmont regions to the southeast, while the coniferous forests of the present northeastern states were limited to a belt paralleling the glacial margin. There is no reason to believe that the general space relation of these five groups has ever been altered, although they must have suffered many fluctuations in their distribution and extent during the preceding glacial advances.

With the retreat of the ice, the new glacial soil was thrown open to migration and speedily covered by plants. Adams has given a picturesque account[6] in general terms of the waves of vegetation which swept on to the north as the ice margin retreated. But postglacial migration was by no means as simple as he has described it, particularly because of the opportunities for migration in easterly and westerly directions as well as toward the north. It is also obvious that the advantage in migration lies with the floristic type located nearest to the new land. Hence it is important to locate the five floristic types as accurately as possible for the time of maximum advance of the Wisconsin ice.

Distribution of Plant Life During the Wisconsin.—When it is considered that the past distribution of plants can in general be interpreted only through circumstantial evidence, it becomes hazardous to venture any opinion on the actual details of plant distribution during this period. Nevertheless certain modern conditions are of interest in this connection.

The glacial drift of southern Illinois beyond the Shelbyville moraine, which marks the southern boundary of the Wisconsin glaciation, is characterized by a large number of more or less xerophytic species. Among these may be mentioned *Ambrosia bidentata, Ascyrum hypericoides, Chamaecrista nictitans, Crotalaria sagittalis, Crotonopsis linearis, Diodia teres, Diospyros virginiana, Galium pilosum, Parsonsia petiolata, Passiflora lutea, Plantago aristata, Plantago virginiana, Quercus marylandica,* and *Quercus stellata.* Few of these are native anywhere within the Wisconsin drift limits, although several of the weedy species have within recent years migrated northward and are now found rather uniformly throughout Illinois. They may be described collectively as xerophytic selections from a southern flora. The same region is also marked by a few rather peculiar xerophytic

selections from a western or southwestern flora, not found elsewhere in the state, such as *Geoprumnon mexicanum* and *Megapterium missouriense,* but it must be noted that these are much fewer than the southern element, and also much fewer than species of the same western element in western Illinois.

Some of the most noteworthy mesophytic trees are nearly or quite absent from the same region, such as *Fagus grandifolia, Cynoxylon floridum, Liriodendron Tulipifera,* and *Magnolia acuminata,* although some of them extend much farther north in almost the same longitude and all of them, crossing Illinois at its southern end, extend westward as far as the Ozark mountains.

The Ozarkian flora at the present time barely reaches Illinois. A few species occur on the rocky hills of the Ozark uplift, such as *Solidago Drummondii* and *Solidago Radula; Trillium viride* occurs northeast of St. Louis, but in general the flora is poorly developed east of the Mississippi, although strongly marked only a few miles west of it. Even such a mobile species as *Vernonia Baldwini,* common in the vicinity of St. Louis, is scarcely known on the Illinois side. There is no evidence as to the date when this flora appeared in Illinois, and no reason to believe that it ever extended farther east or took a more prominent part in the plant life of the region.

In western Illinois, beyond the Wisconsin drift, north of the low range of hills which divided the Illinoian till into two portions (see Leverett's map[30]), and mostly west of the Illinois river, there are a number of intensely xerophytic western species, such as *Bouteloua hirsuta, Bouteloua oligostachya, Schedonnardus paniculatus, Opuntia fragilis, Mentzelia oligosperma, Lesquerella argentea,* and *Cristatella Jamesii.* They are not merely xerophytes, but are limited to peculiar and extreme habitats. They have not been reported east of the terminal moraine, even from similar habitats on the sand dunes of Lake Michigan. *Schedonnardus paniculatus,* with a single station in Illinois, and *Cristatella Jamesii,* with two known stations in Illinois and one in eastern Iowa, present excellent examples of discontinuous distribution, since their nearest stations to the west are 300 to 500 miles away. Such distances are much beyond the normal range of their migration and these eastern stations must be regarded as the relics of a former nearly continuous range across eastern Nebraska and Iowa. This in turn implies a climate some time in the past much drier than at present. There are also in this part of the state a few xerophytic southern plants, such as *Quercus marylandica* and *Crotonopsis elliptica,* but their successional relations indicate a later arrival in the region.

It has been indicated that coniferous plants during the Illinoian glaciation must have been confined to a narrow strip paralleling and adjacent to the ice margin. The same conditions must have obtained during the Wisconsin. The lack of relics of this flora along the Shelbyville and Bloomington moraines is striking. From Edgar County, Illinois, where the terminal moraine enters the state from Indiana, west and north to La Salle County, almost no boreal relics occur. The absence of pines may well be explained by the soil conditions, but the swamps and bayous of the rivers are also without *Larix* and *Thuja* and any of the ericads of the peat bogs of the north; even *Caltha palustris* and *Spathyema foetida* are almost unknown along the glacial boundary until well towards the northern end of the state, although most of these plants are found freely along the moraine in similar latitudes in Ohio and some in Indiana. At the north they reappear: *Abies balsamea* occurs in northeastern Iowa, and *Pinus Strobus* is abundant from southwestern Wisconsin northward. Even *Primula Mistassinica* occurs in northwestern Illinois.

All of these facts of modern distribution may be explained by postulating a glacial climate during the Wisconsin considerably drier than at present and not much different in temperature, so that the vegetation of extra-glacial Illinois assumed a xerophytic aspect. Under this view, we may assume that the Ohio valley in southern Indiana and Illinois was occupied by its present forest flora, possibly not so luxuriantly developed; the Illinoian drift to the north of it by a xerophytic forest of southeastern affinity with a slight admixture, decreasing toward the west, of a prairie element; western Illinois was exclusively prairie, of a type similar to that now prevailing possibly 400 miles farther west. A narrow and interrupted strip of coniferous forest followed the glacial boundary, especially in places where greater topographic relief afforded better shelter. Toward the east, across Indiana and Ohio, the strip became broader and included more species. Toward the north it broadened out again in the driftless area in the shelter of the deep rocky ravines, with the additional protection of the projecting Des Moines lobe of ice extending southward to the west of them. It is doubtful if any conifers or associated species occurred west of this lobe. Tundra vegetation, less affected by the environmental conditions, grew on the thin soil overlying the ice back of the glacial margin. In general, the climatic conditions and vegetation may have been shifted in this latitude 300 to 400 miles east of their present location. The presence of an old flora in the Ozarks indicates that this shift did not extend much farther toward the south.

There is also some geological evidence of a climate during Wisconsin time well suited to a xerophytic vegetation. Various rivers of the region, notably the Wisconsin, the Green, and the Illinois, which rise within the Wisconsin drift and flow out to the west or southwest, occupy beyond the Wisconsin terminal moraine valleys entirely out of proportion to the size of the present rivers and choked with immense quantities of glacial outwash. This may indicate unusually rapid melting, due to a mild (and presumably also a dry) climate.

During this period, forest belts of the more mesophytic species may have existed along the Mississippi, Wabash, Illinois, Missouri, Cedar, and Des Moines rivers in the eastern portion of this semi-arid region, just as they do today in a similar climate in Nebraska and Kansas.

Climate in the Early Post-Wisconsin.—Whether or not the conclusion is accepted that a mild and semi-arid climate existed in the Peorian and persisted through the Wisconsin stages, it seems almost certain that such a climate characterized at least a portion of the time involved in the post-Wisconsin glacial retreat. Palaeontological and geological evidence for such a condition is scanty, and is concisely summarized by various authors in a recent volume.[35] Alden [35a] believes "that during the deposition of the post-Wisconsin loess the climate in the northern interior may have been somewhat drier than at present, but was not greatly different." Knowlton says [35e] "There is some little palaeobotanical support for the contention that there was a slightly warmer period following the close of the glacial epoch." Tyrrell concludes[35f] that the glacial climate of the Canadian northwest was "succeeded by a dry continental climate, under neither of which conditions was a forest growth possible." Basing his opinion on the occurrence of certain animal remains, Hay believes [35d] "that after the retreat of the ice-sheet a warmer period ensued," at the culmination of which "the region along the southern shores of Lakes Ontario, Erie, and Michigan enjoyed a climate similar to that now prevailing in Tennessee

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[35] Die Veränderungen des Klimas seit dem Maximum der letzen Eiszeit. Eine Sammlung von Berichten . . . herausgegeben von dem Exekutivkomitee des 11. Internationalen Geologenkongresses. Stockholm, 1910. Including:

[35a] Alden, Wm. C. Certain geological phenomena indicative of climatic conditions in North America since the maximum of the latest glaciation. 353–363.

[35d] Hay, O. P. On the changes of climate following the disappearance of the Wisconsin ice sheet. 371–374.

[35e] Knowlton, F. H. The climate of North America in late glacial and subsequent post-glacial time. 367–369.

[35f] Tyrrell, J. B. Changes of climate in northwestern Canada since the glacial period. 389–391.

and Arkansas." Similar opinions have also been expressed by Coleman, Matthew, Dawson, Leverett, Upham, and Davis.

The same period was early recognized in Scandinavia by Blytt[36] and has been generally accepted by most European phytogeographers. Of the numerous papers on the subject published in the same volume, those of Andersson [35b-c] seem especially conclusive. He decides that during the early postglacial stages the climate of Scandinavia had winters similar to those of the present, while the summers were longer and about 2.5° C. warmer. Later the climate became wetter, while remaining equally warm, while for the modern period there is evidence of a slow lowering of the temperature. It is also worthy of note that Andersson lays great stress on the value of relic colonies as evidence of past distribution.

The term xerothermic period has long been used by Europeans for this period of mild and drier climate, and may well be extended to the same type of climate, probably contemporaneous, in America.

A xerothermic period, occurring in comparatively recent times, and without any subsequent geological episodes to modify greatly the trend of plant migrations, would certainly have left an impress on the distribution of vegetation which would still be visible. Among the effects which might be expected is a great extension of the prairie flora toward the east, taking advantage of the favorable climate. This should now be evidenced by relic prairie colonies and by isolated stations of western species at the east and by a deficiency of hydrophytic and mesophytic boreal relics at the west. Both of these results are actually demonstrable at the present time, as will be shown below. A third effect should be seen in the migrations of the deciduous forests from the southeastern center, in which the more mesophytic species would be limited at first to a northward migration only, passing to the east of the area affected by xerothermic conditions, while the more xerophytic species would migrate both north and west, accompanied by other species of edaphically moist floodplains, such as now form the westernmost groves of Kansas and Nebraska. Present distribution indicates that this was also a fact, although it is less clearly evident at the present time.

Tundra and Coniferous Forest Migration.—The northern boundary of the tundra vegetation overlying the glacial ice extended toward the north with the retreat of the ice. At its southern boundary,

35b Andersson, Gunnar. Das spätquartäre Klima, eine zusammenfassende Uebersicht. xii-lvi.

35c Andersson, Gunnar. Swedish climate in the late-quaternary period. 247-294.

36 Blytt, Axel. Dia Theorie der wechseluden kontinentalen und insurlaren Klimate. Engler's Bot. Jahrb. 2: 1-50. 1881.

the tundra persisted until destroyed by the warmer climate or by the succession of the coniferous forests. In general, tundra withstands a climate slightly warmer than its optimum better than the competition of forest species, which quickly destroy it by shading.[22] As in all such retreating migrations, relic colonies were isolated, surrounded by the advancing forests, and persisted for a longer or shorter time until finally completely overgrown by the spruces and firs. Naturally those endured the longest which occupied habitats least favorable to forest growth. We may presume that the sand dunes along the shores of the postglacial lakes and such isolated rock outcrops and cliffs as Starved Rock in Illinois and the Dells of the Wisconsin River were for a long time occupied by tundra plants, just as they are now occupied by relics of the coniferous forests. The xerothermic period and ordinary successional processes have long since destroyed the last vestige of tundra vegetation in these latitudes, and the southernmost species are now found scarcely farther south than Lake Superior. On Isle Royale[37] associations still exist which bear a general resemblance to the arctic tundra and contain a few species of distinctly northern distribution. As the tundra migrated northward into cooler and moister regions, and the cooling influence of the ice was felt farther beyond its margin, the belt of tundra broadened, that is, it migrated toward the north faster than it retreated from the south, until it now occupies an area some hundreds of miles wide.

The boreal coniferous forests which had occupied a narrow or interrupted strip along the glacial margin during the Wisconsin stage also migrated northward following the retreat of the glaciers, surrounding the relic colonies of tundra and eventually replacing them by succession. The pioneers in the movement were probably then as now the xerophytic species advancing along the rock outcrops and till of the upland, and the bog species proceeding along the drainage lines and the glacial lakes. These forests also advanced toward the north faster than they retreated from the south, and consequently occupied a strip of increasing breadth. This led to their present dominance over a large area north and east of the Great Lakes and to their temporary dominance, which is still continued in many habitats, in northern Minnesota, Wisconsin, and Michigan. Their northward movement brought the conifers into climates progressively cooler and relatively moister. This led not only to a greater number and size of individuals, but also permitted a northwestward migration into northern Minnesota and Manitoba. This northwestern prolongation was eventually extended,

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[37] Gleason, H. A. The ecological relations of the invertebrate fauna of the Isle Royale, Michigan. Rep. Mich. Geol. Survey 1908: 57-78. 1909.

with the complete disappearance of the land ice, as far as Alaska. Since the morainal strip of boreal vegetation was, in the Middle West at least, always narrow, frequently interrupted, and probably completely absent about the Des Moines lobe, and composed chiefly of a xerophytic selection of species, the western end of the forest belt was composed, during its advance to its present location, of a comparatively meager flora. Each mile of advance to the northward saw the widening of the belt and the junction of portions previously isolated, and consequently permitted a westward migration of species from the eastern states, which were little affected by the xerothermic climate. This westward migration has by no means been completed and is probably even now in progress through the forests of Quebec and Ontario, but the boreal flora of the upper Lake region is still poor in comparison with that of Quebec, New Brunswick, and the New England states. The northwestern extension across Manitoba to Alaska shows a progressive diminution in the number of species concerned, as graphically shown by Transeau's[38] map.

When these forests reached the eastern foothills of the Rocky Mountains in Alberta, they were again in contact with the closely related species of the Pacific Conifer Province, from which they had long been separated. It will be interesting to learn from future studies what exchange of species now took place; whether widely distributed species common to both regions, such as *Populus tremuloides,* had been in both since their segregation; whether the numerous Pacific plants of the St. Lawrence valley are preglacial members of the northeastern flora, or migrated eastward at this comparatively recent stage. It is not too much to expect that all of these matters are possible of solution.

In this migration of boreal plants, numerous relic colonies were left behind. Many of them have since disappeared before the encroachment of surrounding vegetation or the changes in climate, but thousands still exist. As is generally the case with relic colonies, they occupy for the most part extreme habitats, either xerophytic rock hills and sand dunes, clothed with *Pinus Strobus* and *Pinus Banksiana,* or bogs, characterized by *Larix laricina* and *Thuja occidentalis.* It is especially noteworthy that in Ohio, where the influence of xerothermic conditions was reduced by the eastern position, the hydrophytic colonies persist farther south than the xerophytic. In Illinois the condition is reversed, and neither of the two hydrophytic trees is reported from Iowa. Tamarack bogs are found in Illinois only along the borders of deep lakes in the immediate vicinity of Lake Michigan, while *Pinus Strobus*

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38 Transeau, Edgar N. Forest centers of eastern America. Amer. Nat. 39: 875-889. 1905.

occurs not far from the Mississippi and in one county in southeastern Iowa. The occurrence of boreal relics in the driftless area of northeastern Iowa has already been noted.

Ponds were abundant on the Wisconsin drift in Illinois half a century ago, and were notable for the complete lack of such hardy boreal plants as *Comarum palustre, Dulichium arundinaceum,* and *Menyanthes trifoliata.* They were mostly shallow and easily drained and have long since disappeared. They were also characterized by the absence of deep peat deposits, indicating that they had never been occupied by boreal vegetation and were of comparatively recent origin. The carefully prepared reports of the Illinois soil survey present interesting figures concerning them. Ten counties of central Illinois contain only 1,986 acres of deep peat, or 0.04% of their area, and of this 1,779 acres lie in the floodplain of the Illinois River. Three counties of north-central and northern Illinois contain 0.15% of deep peat, one county in the Kankakee valley 0.83%, while three counties of northeastern Illinois contain 4.67%. Even in southern Michigan, far within the boundary of the Wisconsin deposits, only the deeper lakes are bordered by tamarack bogs. This lack of hydrophytic boreal relics toward the southwestern angle of the Wisconsin glaciation is best explained by the assumption of the xerothermic period, as already noted, during which hydrophytic habitats were obliterated toward the west, except in the deepest depressions or in local areas affected by subsurface water,[39] thereby restricting the relic colonies chiefly to the xerophytic types.

Early Migration of the Prairie Flora.—An advance of the prairie vegetation toward the east and northeast followed immediately behind the coniferous forests, displacing the rearguard of the forest by successional processes. There is now no place in the Middle West where grassland is succeeding forest, and it becomes difficult to picture the detailed steps by which such succession proceeded. In bogs, as the climate grew warmer, and the ingress of water was reduced with increasing distance from melting ice, the gradual drying may have inhibited the growth of seedlings and permitted the entrance of prairie species. This process is now seen in modified form in southern Michigan, where partial drainage of tamarack bogs leads to the displacement of the usual bog shrubs by *Dasiphora fruticosa.* On uplands, the exposure of the marginal trees to warm and dry winds during the summer, with consequent injury through excessive transpiration, may

[39] Gates, F. C. A bog in central Illinois. Torreya 11: 205-211. 1911.

have had the same effect,[40] while severe winter-killing among young plants may have resulted from deficient snow cover.[41,42]. Certainly the fewest boreal relic colonies are now found in southern Wisconsin and southeastern Minnesota,[43] where such atmospheric conditions are still more or less in effect.* Geographically the advance of the prairies was favored by the slow withdrawal of the eastern ice northward and the rapid retreat of the western ice northeastward, thereby opening to invasion first Illinois and then Indiana. A slight change in the nature of the ice retreat might have affected the future vegetational development of the region very greatly.

The distance to which the prairie vegetation migrated northward is not definitely known. Very likely it reached in central Michigan as far as the jack pine plains, which still contain numerous prairie species, and if this is true must have reached similar or even higher latitudes in Wisconsin. There is no present reason to believe that prairies were developed on the north shore of Lake Erie. Deciduous forests in Minnesota now occupy a narrow strip between the prairie and the coniferous forests, and it is probable that their entrance was about equally at the expense of the two earlier types of vegetation. If this is true, the prairies did not extend much beyond their present range in that state.

The eastern migration of the prairie proceeded as a wedge-shaped extension between the coniferous vegetation at the north and the deciduous forests at the south and reached limits considerably beyond the eastern margin of modern continuous prairies. Numerous relic colonies formerly occurred, before they were destroyed by agriculture, in eastern Indiana, northwestern Ohio, and southern Michigan[44] (see also Cooper's description of an oak opening in his novel of the same name). Vegetation closely simulating typical prairie exists along the Scioto River near Columbus, Ohio. Bonser[45] has described a marshy tract near Sandusky, Ohio, which still contains some western species, notably *Vernonia fasciculata*. This so-called prairie has doubtless

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* Contrast maps in references 37 and 42.

40 Shimek, B. The prairies. Bull. Lab. Nat. Hist. Univ. Iowa 6^2: 169-240. 1911.

41 Gates, F. C. The relation of snow cover to winter killing in *Chamaedaphne calyculata*. Torreya 12: 257-262. 1912.

42 Gates, F. C. Winter as a factor in the xerophily of certain evergreen ericads Bot. Gaz. 57: 445–489. 1914.

43 Livingston, B. E. A study of the relation between summer evaporation intensity and the centers of plant distribution in the United States. Plant World 14: 205–222. 1911.

44 Gleason, H. A. A prairie near Ann Arbor, Michigan. Rhodora 19: 163-165. 1917.

45 Bonser, Thomas A. Ecological study of Big Spring Prairie, Wyandot County, Ohio. Ohio Acad. Sci. Special Paper 7. 1903.

preserved its hydrophytic environment since an early period, being watered by springs, and consequently contains a considerable number of boreal species, notably *Betula pumila*. *Opuntia humifusa* occurs near the same place. Species of distinctly western affinities do not occur on Presque Isle, near Erie, Pennsylvania,[46] and the abundant development of boreal species and the typically Alleghenian aspect of the flora in northeastern Ohio make it reasonably certain that extensive prairies were not developed east of Cleveland.

The unglaciated areas of southern Ohio, Indiana, and Illinois, and the Ozark region of southern Missouri are now populated with a forest flora that presents indications of great antiquity, and in their greater topographical relief offer better opportunities for forest species to endure unfavorable atmospheric conditions. It seems reasonably certain that the prairies did not encroach on this area at any time. Probably the southern boundary of the glaciated area marked the division between forest and prairie, and probably forest belts followed even then the courses of the rivers northward well into the prairie region. The forest belts of the Mississippi may have been derived from the southern species of the Mississippi embayment; at the present time several of them follow the course of this river northward, such as *Gleditsia aquatica* and *Hicoria Pecan*. No evidence is now at hand concerning the possible extent of the prairie into the Ozark region of southwestern Missouri and northwestern Arkansas. What relation the xerothermic period may have had to the barrens of Tennessee, the prairie belt of central Alabama, the prairies of eastern Arkansas, and the coastal prairies of Louisiana must be left to the deductions of observers who have had personal experience with the vegetation of these areas.

In further support of the idea of a xerothermic period, it need only be recalled that the discontinuous distribution of such plants as *Opuntia fragilis* and *O. humifusa*, *Sporobolus heterolepis*, *Cristatella Jamesii*, and *Callirrhoe triangulata* can be adequately explained only by assuming a former period of climate sufficiently drier than the present to permit their continuous migration. This, with the existence of relic prairie colonies at the east and the prevailingly xerophytic nature of the relic boreal colonies at the west, seems to be sufficient evidence of the actuality of a post-Wisconsin xerothermic period.

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46 Jennings, Otto E. A botanical survey of Presque Isle, Erie County, Pennsylvania. Annals Carnegie Mus. 5: 289–421. 1909.

The eastward advance of the prairies was either accompanied or followed by some specific evolution among the species participating, as indicated by such plants as *Phymosia remota,*[47] *Synthyris Bullii,* and *Tetraneuris herbacea.* These plants are now confined to the eastern arm of the Prairie Province, but in each case have their nearest related species much farther west.

There is no reason to suppose that the xerothermic period came to a sudden close, which would require an equally sudden geological event in explanation. In fact, it may have been most pronounced during the Wisconsin glaciation and diminished in intensity ever since, but not sufficiently to check the rapid advance of the prairies behind the retreating coniferous forests. Neither can the time of maximum advance of the prairies be correlated at present with the postglacial stages of the Great Lakes.

EARLY MIGRATIONS OF THE DECIDUOUS FORESTS.—At some time an amelioration of the climate began. This change was probably less connected with temperature, which has doubtless changed but little in our area since the Wisconsin glaciation, than with rainfall and atmospheric humidity. The total rainfall probably increased considerably, but the increase fell chiefly during the winter months and changed the climate from one of summer rains, such as is now characteristic of the prairies farther west, to one of fairly equable rainfall. This change first made itself felt in the east and gradually progressed toward the west. At the present time, each hundred miles west of the Wabash River along the fortieth parallel shows a marked diminution in winter rainfall.

The effect of this climatic change was the retardation and eventual cessation of the old successional relation between coniferous forest and prairie, soon followed by a break in the equilibrium along the southern and eastern margins of the prairies, leading to an advance of the deciduous forests northward and westward.

Two general routes were followed in this forest migration, a northward and westward route from the forests along the southern edge of the prairies and a northward and then northwestward route from those lying east of the easternmost extension of the prairies. Many species were common to both regions and participated in both migrations; others were localized and show by their present distribution that they entered the Middle West by only one of these routes. Both took place simultaneously, and in some places both migrations eventually met,

[47] Clute, W. N. The rarest American Plant. Amer. Botanist 26: 127–129. 1920.

so that races of similar ultimate ancestry but of different recent history are again growing together.

The Southern Migration.—The southern migration was participated in chiefly by oaks and hickories of the drier uplands, and by oaks, elms, ashes, walnuts, maples, hackberry, cottonwood, honey locust, coffee tree, buckeye, and sycamore of the lowlands. Following as closely behind the prairies as environmental change would permit, these plants established two successional series, a xerarch series on the uplands, leading to the establishment of an oak-hickory forest, and a hydrarch series along the stream valleys, leading to the development of marginal belts of hydrophytic or mesophytic forest. The hydrarch series migrated more rapidly up the stream courses, since the species concerned could take advantage of local conditions of favorable moisture, while the xerarch series found its most favorable route along the broken topography of the river bluffs, between the prairies above and the hydrarch forests below. The two types of forest thus advanced upon the prairies together along the river courses leading southward into the Ohio valley and eastward into the Mississippi, and the present outposts of this migration are still to be seen in Kansas, Nebraska, the Dakotas, and Manitoba on the west and in Michigan and Wisconsin on the north.

Some of the mesophytes were left far behind in this advance, and the beech, sugar maple, tulip tree, and basswood are not particularly important members of the climax forest or even totally absent from Illinois west. In such cases a temporary climax developed in ravines and on floodplains and was composed chiefly of a selection of species persisting from the earlier successional stages. The slower trees have been migrating, nevertheless, and with the greater success the farther east. Beech is common in the Ohio valley: it has scarcely moved up the Mississippi, but has followed the Wabash well into Indiana, and the Miami, Muskingum, and Scioto until Ohio is occupied by it completely. There is reason to believe[48] that large areas of forest were developed on the uplands in which the most mesophytic tree was the red oak, *Quercus rubra.*

The Northern Migration.—The northern migration proceeded from the deciduous forests which had had a glacial center of preservation in the Allegheny Mountains from Pennsylvania southward. These species, now constituting the well known Alleghenian element in the flora of New York and New England, have been during and since the

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[48] Gleason, H. A. An isolated prairie grove and its phytogeographical significance. Bot. Gaz. 53: 38–49. 1912.

glacial period more or less mixed with boreal elements, and this condition has been increased by their postglacial migration into a country from which the coniferous forests were retreating and leaving numerous relics behind, without an intervening prairie stage. Moving slowly northward behind the glaciers, which occupied the Ontario basin long after migration routes farther west were open, a portion of the species concerned finally turned to the west and northwest and entered Michigan, Wisconsin, and Minnesota, while others, such as *Quercus Prinus,* moved scarcely west of the Appalachian region.

It has not been possible so far to form an opinion as to the particular postglacial stage of the Great Lakes when this westward turn took place. It may have been in a narrow strip between the prairies and the coniferous forests, following the former to the north and broadening out only after reaching relatively high latitudes, in which case it could have occurred at an early postglacial stage, or it may be a more recent movement, even as late as the Nipissing stage, in which case it might have passed to the north of Lake Erie and entered Michigan by crossing the Detroit and St. Mary's rivers.

The Combined Effects.—The two migrations together may be compared to a vast U, with its base in the southern Alleghenies, one side extending as far west as the Ozarks, and the other passing northwest to Minnesota. The northern migrants have shown little tendency to move southward, especially toward the western part of their route, while the southern ones have moved steadily northward until their outposts have entered the area of the northern arm in Michigan and Wisconsin, where oak, sassafras, and sycamore occur in the same area with sugar maple, beech, and white pine. The base of the U has gradually closed over Ohio and part of Indiana, chiefly through immigration from the south. As a result there is little difference between the forests of southern Michigan and those of any part of glaciated Indiana. The valley of the Grand River in central Michigan is a well marked division line between forests of the two types, according to observations of B. E. Quick, and above it the deciduous forests are derived mostly from the northern migration.

Migration and Evolution.—The forest migration was accompanied by specific evolution also, and various species have been described from the forest region of the Middle West. In most cases their probable evolution is in doubt, from lack of careful study, but Dr. F. W. Pennell has kindly supplied certain cases among the Scrophulariaceae in which the ancestry of the species or varieties seems reasonably certain. Thus *Agalinis paupercula* of the glaciated region is considered as derived

from *A. purpurea; Aureolaria Pedicularia* (L.) Raf. (*Dasystoma Pedicularia*) has given rise to the variety *ambigens* (Fernald) of the Middle West. In other cases, the parent species, existing through the glacial period south of the ice margin, has followed both routes of migration and in so doing has become segregated into a pair of closely related forms, one of which took the southern route leading northward from the Ohio valley and the other the northern route along the Alleghenies and the Great Lakes. Thus *Trillium nivale, T. declinatum*, and *Cynoglossum virginianum* of the southern portion of the Middle West are paired with *Trillium undulatum, T. cernuum,* and *C. boreale* respectively of the northern portion.

Changes in the prairie flora took place at the same time. Distinctly western species withdrew entirely from the eastern extension or, like *Cristatella Jamesii* and others already mentioned, left relics behind in especially favorable xerophytic habitats. Relic colonies were isolated throughout the region, many of which still persist. These were subject to slow but persistent succession by the forests; many must have been obliterated, while others were greatly reduced in size.

Prairie and Boreal Relics.—The nature and location of these prairie relics and of the boreal relics in the same area may yet give a clue for the better understanding of the period and route of the northern migration of deciduous forests. There is in general a great difference in environment between forested and unforested habitats, such as a prairie and either a coniferous or a deciduous forest. Differences also exist between the two types of forest, but these are of less importance and to many species of little significance. Boreal relics, therefore, have not commonly persisted in the prairie, but remained in definite colonies. Similarly, prairie relics have been confined largely to colonies and have not persisted as scattered plants within the invading deciduous forests.[49] So, wherever the deciduous forests have succeeded the coniferous forests directly, numerous boreal species persisting to the present time bear evidence of the fact. These are of common occurrence in southeastern Michigan and indicate that the prairies were not universal there, but are rare or lacking in Illinois and Indiana, showing that the coniferous forests had disappeared before the advent of the deciduous trees from the south. Relic colonies, as has been pointed out before, remain in habitats not necessarily favorable to themselves, but unfavorable to the invaders. Consequently, prairie and boreal relics sometimes occupy the same station, into which they have been

[49] Vestal, Arthur G. Local inclusions of prairie within forest. Trans. Illinois Acad. Sci. 11: 122–126. 1918.

The writer has no doubt that further study of the problem of glacial and postglacial vegetational history, based on additional facts of modern distribution, on better knowledge of plant migration and the ecological requirements of species, and on new evidence from fossils, and carried on by investigators with different viewpoints and different personal experiences, will lead to many important modifications of the outline here presented. The field is large, almost untouched, and of compelling interest, and it is hoped that it will attract the attention of students not only in the region here discussed, but elsewhere through the country as well.

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SHORE CHANGES AT CAPE HATTERAS

G. T. RUDE

CONTENTS

Introduction.— Since volumes have been written on shore processes, it is evident that in a limited discussion little is to be gained by a general and purely theoretical consideration of the subject, and it has been elected, therefore, in the preparation of this short paper to take a particular locality and attempt to show by quantitative data a correlation between shoreline changes and local storm data. I am indebted to the officials of the U. S. Weather Bureau for their courtesy in allowing me the privilege of consulting original records from their meteorological station at Cape Hatteras for the period — 1875 to the present time.

Since the results of the surveys which are obtainable for the purpose of showing the changes in the shoreline of Cape Hatteras at different periods somewhat antedate available meteorological data, final conclusions to the second decimal place are not to be expected, and it is hoped that this discussion will be considered as the beginning only of a collection of quantitative data, which may in time be supplemented, tending finally toward conclusive results along these lines.

As is the case in practically all research work along oceanographic, geologic, geophysical and many other lines, there is a dearth of data of a quantitative nature over even the relatively short period covered by this study, and it has been necessary to employ mean values over a large part of the period.

Current and Wave Action.— While currents undoubtedly play a large part in shoreline changes, they may be considered only the transporting agents and not the cause of the changes, the impact and backwash of storm waves being the direct causes, furnishing the material to wind-driven currents, not tidal currents. (The writer is not unmindful of a type of currents in waves and in wave action itself, but these, too, are relegated to subordinate positions as direct agents; the power in

wave impact being considered the principal agent.) In general, coastal tidal currents except at the immediate entrances to estuaries are of small velocity—seldom exceeding two or three tenths of a knot,—while alongshore wind-driven currents may attain a velocity at times of one to one and a half knots.

Of course, the conditions outlined above are for the exposed coasts and not for rivers or straits. In these cases we have, in the former, freshet currents cutting at the outer bends and depositing the material in the sluggish waters in the inner bends and on the deltas; in the latter we have action of a current not strictly tidal. In the East River, for example, strong currents have swept the channel to bedrock, depositing the material in the quieter bays and coves along its banks. These currents, however, are not tidal currents of the purely rotary or progressive type, but rather are hydraulic currents due to difference in head between the waters of Long Island Sound and New York Bay.

It therefore appears safe to assert that, in general, impact of wave action is the prime factor in shoreline changes on the open coast and wind-driven currents the secondary factor or transporting agent.

For this particular study the Atlantic coast has been taken in the immediate vicinity of Cape Hatteras. Attention is called to the arc of exposure to the Atlantic storms—from north practically to southwest by way of east. While length of fetch is accepted as a factor in shore changes, it does not enter into this discussion, since the fetch over this arc is of sufficient length to preclude it from the consideration.

The Wind and Storm Data.— In arranging the prevailing wind data, including storm winds, (Table A), the mean yearly wind movement has been taken from the original meteorological records of the Cape Hatteras Weather Bureau station for the past 50 years for each cardinal and inter-cardinal point and resultants secured which, in addition to the tabulated values in Table A for 10 year periods, are shown graphically at the top in Fig. 1 by the arrows, their lengths representing the relative strengths of the different components, the solid arrows through the arc of exposure and the skeleton arrows through the protected or shore arc. The marked southerly component may be noted; this fact will *partly* explain the total southerly progression of the shoreline on the extreme point at Cape Hatteras as shown in Figure 1. Unfortunately, no meteorological data are available prior to 1875.

The arrows near the center in Figure 1 represent graphically the resultants of the *storm winds* for the 21 year period from 1900 to 1920. Here, too unfortunately, the storm wind data extend back only over a short period — to the year 1900. These storm wind data are also tabulated in Table C.

In arranging the storm data the United States Weather Bureau's

definition of a storm wind has been accepted. This velocity is now taken at 40 miles per hour; that is, this velocity is attained each hour and maintained for at least five minutes, and storm warning signals are displayed for winds of that velocity. Prior to 1906, it was 33 miles per hour; therefore for the purposes of this discussion the latter figure was taken through the entire period in order to make the two periods comparable.

The arrows, then, and the tabulated values in Table C show the resultant forces of such storm winds for a period of 21 years, the length of the arrows and the numbers indicating the relative strengths of resultants, the skeleton arrows in the protected arc and the solid in the exposed arc, as in the case of the prevailing wind arrows.

In summing the storm-wind velocity-hours for each cardinal and inter-cardinal point for this period, only those hours were taken which were of a 33-mile velocity or over, and then only for days during which the total wind movement aggregated 600 wind-velocity-mile hours or more; that is, a squall of just a few hours duration was neglected for the reason that no sizeable sea is likely to be created by such a squall. Since the total wind movement for different days varies from about 100 velocity-mile hours to about 1200, 600 was taken as the minimum total wind movement which would best define a storm day. Instead of summing the absolute velocity values for the different hours, in the case of storm winds, the number of storm hours were summed for each cardinal and inter-cardinal point.

In Table B are shown the resultants for each cardinal and inter-cardinal point of the storm winds for different periods. For comparison the period 1900 to 1920 has been separated into two periods — 1900 to 1910 and 1910 to 1920. Considering the variability of storms it is remarkable how closely the resultants agree when taken over long periods. The information conveyed by the quantitative data in Table B would tend to indicate that the force exerted on this coast line by storm wind-waves is not the variable[1] factor ascribed to it, nor that the prevailing winds are offshore and the greater storms from the south and west[2].

Resultants for the year 1909 are shown in order to call attention to the striking variation from the mean of the values for the northeast and southwest — 16 to 53, the only year over the whole period in which the southwest resultant equalled or even approached the value of the northeast, and this year it will be seen that it has over three times the strength of the northeast component.

Quantitative Measurements of Changes of Shore Form.—Figure 1 shows the shore changes at Cape Hatteras during the past 71 years, as secured from surveys made in 1850, 1852, 1860, 1872, 1917, and

[1] Haupt, p. 149, Proc. Am. Phil. Soc. XXVI, 1889.

[2] Haupt, p. 155, Proc. Am. Phil. Soc. XXVI, 1889.

1921. Along the straight shoreline where there has been a consistent recession apparently during the entire period, the average movement each year from 1917 to 1921 has been *11 yards.* A comparison of the storm wind resultants shown in Table B for this period over the arc of exposure from north to south with those of period 1875 to 1917 is as

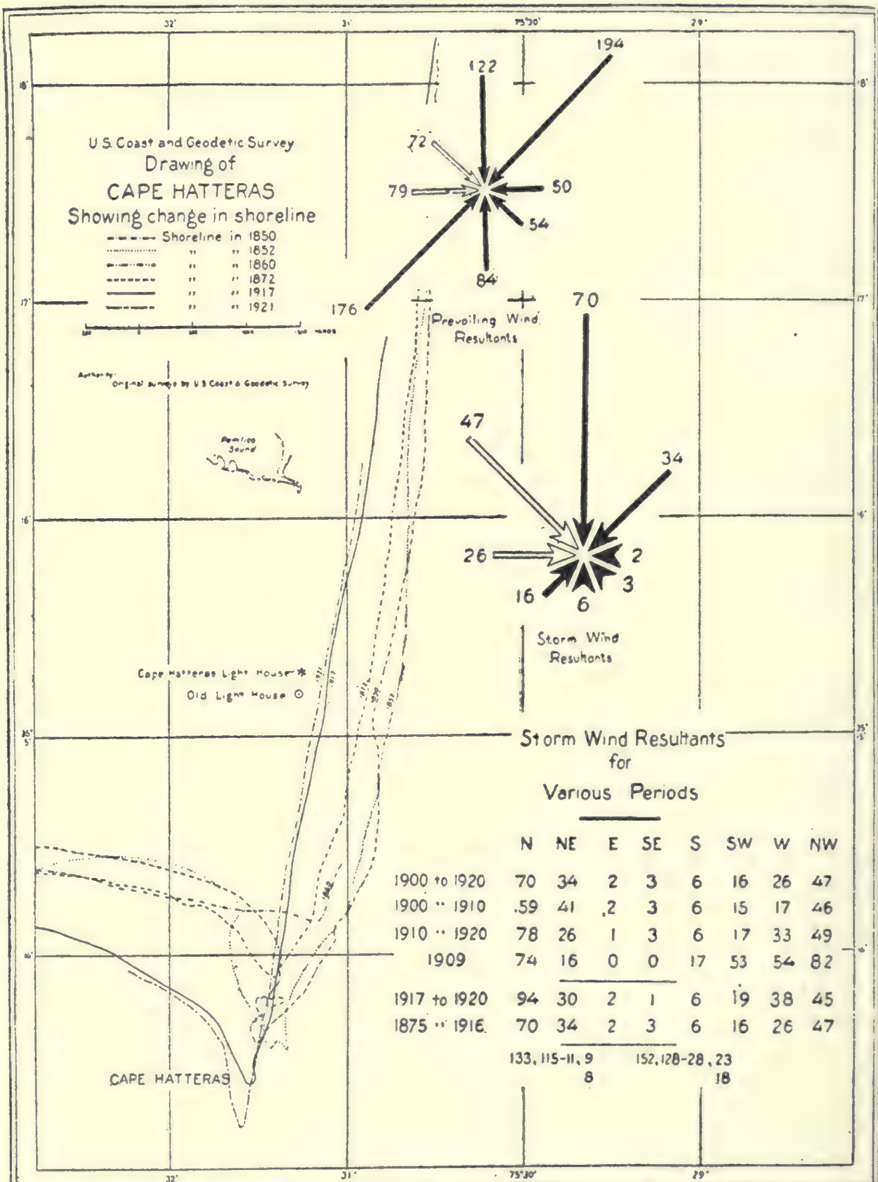

Fig. 1.—Map of changes at Cape Hatteras

TABLE A.

PREVAILING WIND MOVEMENT, CAPE HATTERAS METEOROLOGICAL STATION.
Ten Year Averages for the Period 1875 to 1920.

Period	Average Yearly Total Wind Movement	Average relative frequency of winds from							
	Mile hours	N.	N. E.	E.	S. E.	S.	S. W.	W.	N.W.
1875–1884	120390	95	340	62	95	87	224	76	81
1885–1894	116295	167	160	52	47	121	155	95	80
1895–1904	122474	137	153	43	46	79	144	86	66
1905–1914	128216	94	166	44	43	60	189	69	72
*1915–1920	129380	118	149	52	41	72	167	69	63
	Means	122	194	50	54	84	176	79	72

* 4 years, record for 1918–19 in use, not available.

TABLE B.

STORM WIND RESULTANTS FOR DIFFERENT PERIODS.

Period	Average number of Storm Hours with winds from							
	N.	N. E.	E.	S. E.	S.	S. W.	W.	N. W.
1900 to 1920	70	34	2	3	6	16	26	47
1900 to 1910	59	41	2	3	6	15	17	46
1910 to 1920	78	26	1	3	6	17	33	49
1909	74	16	0	0	17	53	54	82
1917 to 1920	94	30	2	1	6	19	38	45
*1875 to 1916	70	34	2	3	6	16	26	47

* Using mean values prior to 1900.

TABLE C.

YEARLY STORM WIND RESULTANTS FOR THE PERIOD.

1900 to 1920.

Year	Number of storm hours with winds from							
	N.	N. E.	E.	S. E.	S.	S. W.	W.	N. W.
1900	47	0	1	7	3	13	43	36
1901	69	1	0	0	4	1	18	70
1902	28	29	2	0	2	9	7	20
1903	128	42	4	7	1	34	5	24
1904	10	6	3	0	1	12	13	12
1905	69	38	0	2	9	2	16	32
1906	121	103	4	0	9	1	0	13
1907	31	108	0	7	3	8	8	67
1908	37	85	11	6	15	20	21	86
1909	74	16	0	0	17	53	54	82
1910	31	28	0	0	2	10	2	64
1911	41	5	0	0	3	12	12	44
1912	66	35	0	0	15	21	37	73
1913	33	23	3	7	10	25	17	38
1914	119	14	0	15	2	16	47	39
1915	70	47	3	5	6	11	75	33
1916	123	20	0	0	1	13	21	66
1917	96	32	3	3	10	16	65	74
1918	98	26	6	2	6	37	15	29
1919	86	15	0	0	0	0	21	27
1920	96	45	0	0	9	22	53	50
Means	70	34	2	3	6	16	26	47

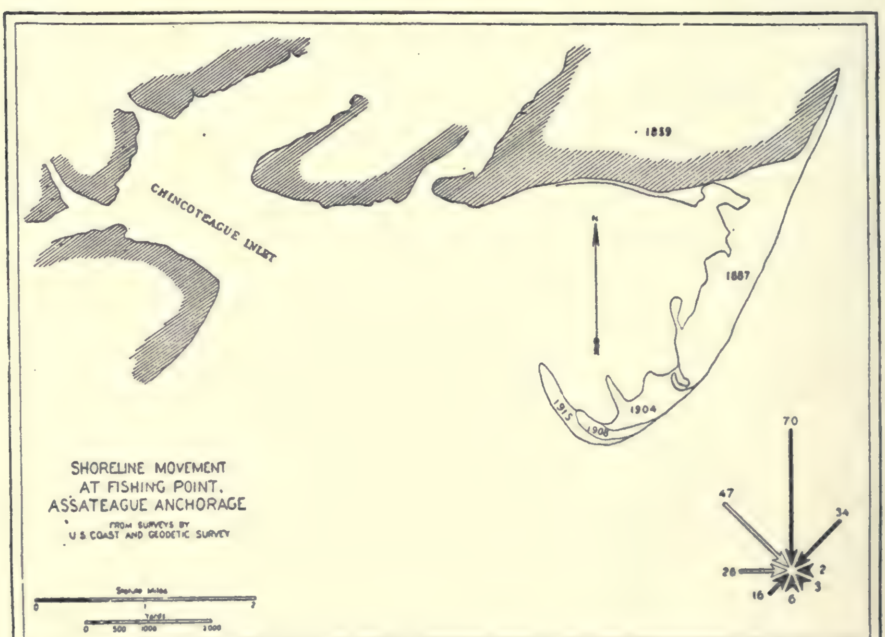

FIG. 2.—Shoreline movement as Assateague Anchorage

133 is to *115,* using actual values back to 1900 and mean values prior to that year, for the reason that no data are available previous to that time. Introducing these factors and the average movement of *11 yards* for the period 1917 to 1921, into a proportion gives a computed movement of *9 yards* each year for the earlier period, while the actual mean movement as measured every half mile along the coast is *8 yards* each year for that period.

Now, during the period between two early surveys at Cape Hatteras (1850 to 1860), a recession of the shoreline on the point occurred (Fig. 1), where there has since been a steady progression at that point. Unfortunately the recession at the extreme point occurred prior to the availability of meteorological records, but this recession may be explained by reference to the data for the year 1909 which, as shown in Table C, has a strong northerly resultant, and the recession may have been due to several such years during that periol for which no records are available.

For changes in the shoreline on the south side of the point the storm winds over the whole arc of exposure have been considered. A comparison of these resultants for the period, 1917 to 1920, with the earlier period, 1875 to 1916, are as *152* is to *128,* and the average yearly shoreline change has been *28 yards* each year for the later period. Introducing these factors and the *28 yards* into a proportion gives a computed change on the point for the earlier period of *23 yards* per year, while the actual change has been *18 yards.*

As a matter of interest, changes at Assateague Anchorage, Va., are shown in Fig. 2 for the period 1859 to 1915, as secured from the results of surveys made in 1859, 1887, 1904, 1908 and 1915. Here we have a marked southerly progression of the point, making an excellent harbor of refuge where half a century ago the broad Atlantic rolled in. In the lower right, Fig. 2, are also shown graphically the storm wind resultants obtained at the Cape Hatteras Meteorological Station and while they may not apply exactly to this locality, they undoubtedly indicate the general storm conditions along this stretch of coast.

It is questionable whether further study even will allow of quantitative results in the case of Assateague Anchorage; for the reason that conditions are constantly changing as the point builds to the southward, and it may be that many of the factors cannot be evaluated.

When the point was in the 1859 position the entrance into Chincoteague Inlet was relatively wide and therefore the tidal and storm-driven currents entering the inlet comparatively weak. As the point builds to the southward this entrance is gradually narrowing and these currents therefore becoming stronger at the entrance, causing the point to curve in more sharply at each survey. An inspection of

Figure 2 will show indications of the remains of the earlier curves. It probably may be safely predicted that in another 50 years or so the point which was shown to be curving sharply to the northward in the survey of 1915 will have closed across to the other shore and Assateague Anchorage filled in, the whole point then taking somewhat the same form as Cape May at the entrance to the Delaware, which may likely have been built up as this point is building. Cape May has ceased to build now that the currents entering the bay have become too strong for the material to settle and consequently it passes on into and up the bay to help build up the bars for which that bay is noted.

A similar condition at Assateague makes it difficult to evaluate all factors. If the material brought along the coast by wave and current action were deposited at the point, as a large part of it was in 1859, it would be a fairly simple matter; but much of this material, and in increasing amounts, is swept on into Chincoteague Inlet by currents entering past this point.

Further study of a quantitative nature at the entrance to estuaries on the open coast, taking into account the degree of narrowing at the entrance and actual current observations, may lead to interesting conclusions. This will require, however, more extensive meteorological and current data than now available.

Effects of Tidal Action.—The changes in the shoreline of Cape Hatteras have been treated by some investigators in a manner somewhat different from that attempted by the present writer. It is thought undue importance has been attributed to "On- and offshore tidal action," "Flood tide action," and "Back-set eddies" in the building or changing of this shoreline. The material attributed by some authors[3] as coming from seaward for deposit on the cape has undoubtedly been transferred from the shoreline north of the cape by storm wave action and alongshore wind-driven currents—coming from seaward only in that it swings shoreward into the comparatively quiet waters of the bight south of the cape after passing the point during northerly storms which prevail along this coast. The recession of the shoreline north of the cape is indicative of the source of this material which is added to the cape on its south side.

Regarding "On- and offshore tidal action" and "Flood tide action,"[4] sand will be driven along the bottom if the velocity there be 0.4 knot; fine gravel, if about 1 knot; shingle, about 1 inch in diameter, if 2.5 knots; angular stones, about 1½ inches in diameter, if 3.5 knots[5].

[3] Gulliver, Proc. Am. Acad. A. S. XXXIV, 1899.

[4] Haupt, Proc. Am. Phil. Soc., XXVI, 1889.

[5] Harris, Manual of Tides, 1894–1907.

From observations made at Diamond Shoals Light vessel, located about 25 miles off Cape Hatteras the *tidal* current is about 0.1 knot, and at Frying Pan Shoals Light vessel, located about 20 miles off Cape Fear, the *tidal* current is about 0.4 knot. From current observations made over a long period on the light vessels along the coast it has been found that currents generated by *winds* attain a velocity in knots per hour equal to 1½ per cent of the wind velocity in miles per hour in a direction about 20° to the right of the wind direction. For example, a northeast storm with a wind velocity of 75 miles per hour will create on the Atlantic coast a current of about 1.2 knots per hour setting about W.S.W. It will be seen therefore that not only are *storm winds* on the exposed coast almost as invariable as *tidal* action but also that the currents they generate are far more effective in the movement of ocean floor material than the weaker tidal currents.

THE SIGNIFICANT FACTORS.—In conclusion, we may consider briefly "Back-set eddies."[6] It is very probable that, if such eddies from the Gulf Stream did exist, they would have explained very nicely the formation of this cuspate cape; but current observations over the continental shelf tend to disprove this hypothesis. Instead of assuming a non-existent northeast—southwest *eddy* current effect, we find the prevailing *storm winds* produce a prevailing southwest set. This set changes, however, at times when storms come from other quarters, for they, too, carry their current during the time they are blowing.

The writer during two winters, 1915-16 and 1916-17, was engaged on off-shore hydrographic work from the Carolinas well down the Florida coast and from the shore out to the Gulf Stream, involving the securing of current observations over this area. An analysis of the current observations on the continental shelf show in all cases the rotary tidal current, and also a set with the local wind prevailing at the time of observation. In cases where observations were made at the same anchorage at different times and under different wind conditions the set of the current agreed with the wind blowing at the time. If the direction of the wind at an anchorage was opposite to that at the time of previous observations the set of the current was opposite to the set of the current at the previous time.

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[6] Abbe, Proc. Bost. Soc. Nat. Hist., XXVI, 1895

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THE BARRIER REEF OF TAGULA, NEW GUINEA

W. M. DAVIS

CONTENTS.

SUMMARY.—Tagula, the largest member of the Louisiade archipelago east of New Guinea, is a mountainous island, 30 miles long by nine wide, and 2645 feet in height. Like its neighbors, it is composed of deformed and greatly eroded schists and slates; all the shore lines are embayed; hence the islands may be regarded as parts of a long mountain range of similar structure in northern New Guinea, which have been isolated by strong subsidence. Tagula stands in the eastern part of a vast lagoon enclosed by a great barrier reef, measuring 112 by 30 miles; the western part of the lagoon is divided into a northern and a southern compartment by a chain of small satellite islands; the lagoon floor in each compartment is a smooth plain with maximum depths of 49 and 46 fathoms in the broadest parts. The narrower parts of the lagoon are shallower, evidently because a given quantity of inwashed reef detritus has there caused a greater aggradation. An exceptional feature is the occurrence of 26 minute islets, mostly from 40 to 150 feet high, probably residuals of a former elevated reef, in the northwestern half of the present reef. Two smaller barrier reefs and a few small atolls with shallower lagoons are found near by. The less depth of these lagoons, like that of the narrower parts of the Tagula lagoon, is undoubtedly due to the greater efficiency of aggradation by inwashed reef detritus in lagoons of small area. Not far to the north,

Misima, a mountainous island, measuring 22 by 10 miles, with a height of 3500 feet, has no barrier reef but is terraced by several uncomformable elevated reefs; hence in addition to the general subsidence of the region as indicated by the isolation of its parts, this island has suffered upheaval in recent time.

The smooth floor of the Tagula lagoon cannot be due to the presence beneath it of a smooth platform abraded during the lower stands of the ocean in the Glacial period, because the survival of the minute islands in the barrier reef and the absence of spur-end cliffs on the larger islands prove that no extensive abrasion, either by the normal ocean or by the lowered ocean of the Glacial period, has taken place. Hence the islands must have been protected by living reefs all through

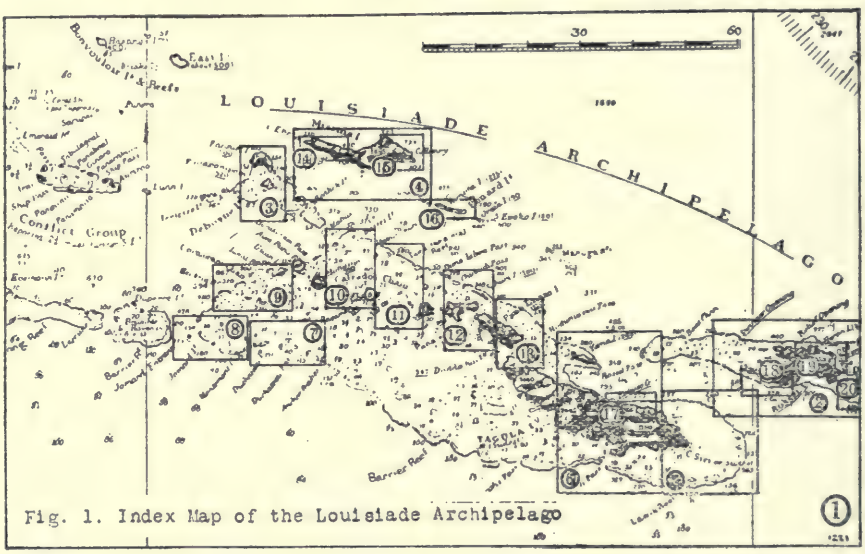

Fig. 1. Index Map of the Louisiade Archipelago

the Glacial period. The depths of the Louisiade lagoons are essentially accordant with the depths of lagoons of similar size in the open Pacific. Hence as the reefs in this region of demonstrated subsidence appear to have been formed by upgrowth from island foundations of uneven form, and as the lagoons within the reefs appear to have been given smooth floors of ordinary depths by the inwash of reef detritus without the aid of abraded sub-lagoon platforms, it follows that similar processes may have produced the similar reefs and lagoon floors of the open Pacific; and, further, that stability of reef foundations and the abrasion of sub-lagoon platforms at a standard depth, as assumed in the Glacial-control theory of coral reefs, are no more essential in the open Pacific than in the Louisiade archipelago. In other words, the Louisiade reefs and lagoons give strong support to Darwin's theory of reef upgrowth

and lagoon aggradation on subsiding foundations; and thus warrant the acceptance of that theory for many other reefs and lagoons—and especially for atolls—in regions where evidence as to the stability or instability of foundations and as to action or inaction of low-level abrasion in the Glacial period is either less decisive or wanting.

CHARTED FACTS CONCERNING TAGULA AND ITS REEF.—This paper is based upon a study of published maps and charts, of sketches, and a few of geological notes made by scientific observers who have visited the island. The Louisiade archipelago as a whole is shown on a small scale in Figure 1, which reproduces a part of Hydrographic Office

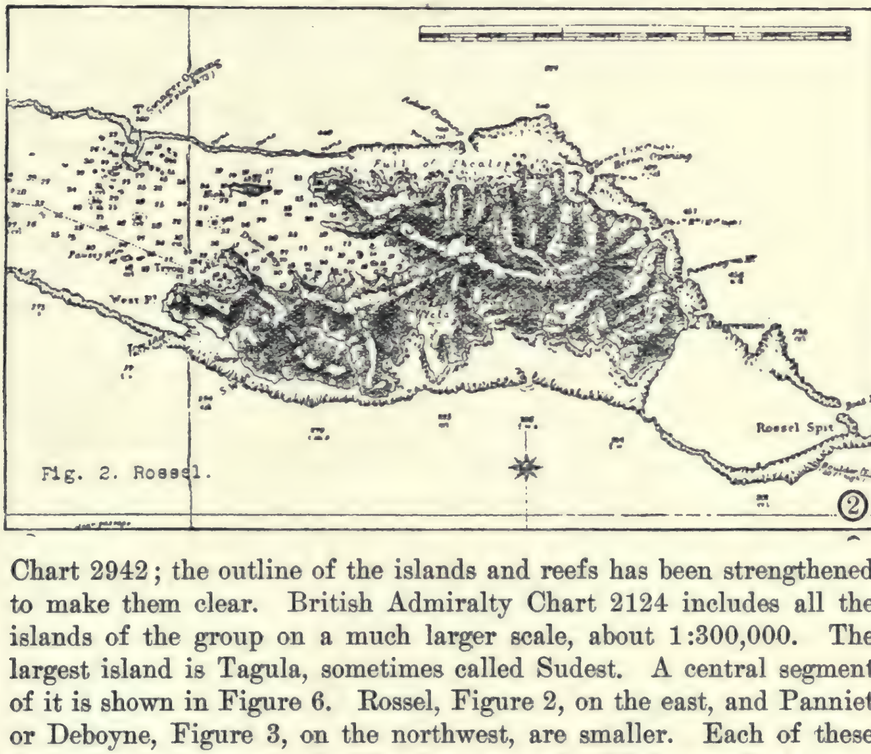

Fig. 2. Rossel.

Chart 2942; the outline of the islands and reefs has been strengthened to make them clear. British Admiralty Chart 2124 includes all the islands of the group on a much larger scale, about 1:300,000. The largest island is Tagula, sometimes called Sudest. A central segment of it is shown in Figure 6. Rossel, Figure 2, on the east, and Panniet or Deboyne, Figure 3, on the northwest, are smaller. Each of these three islands is associated with a barrier reef. Misima or St Aignan, Figure 4, lies farther north and is peculiar in descending rapidly into deep water, without either fringing or barrier reefs; but it bears elevated fringing reefs. B. A. Chart 1477, on a still larger scale of 1:133,000, includes the northwestern part of Tagula and of its great barrier reef, as well as Deboyne and Misima on the north. Several rectangles from this beautiful chart are here produced in Figures 7 to 13. Another B. A. chart, 1473, shows Rossel on a similarly large scale; Figures 17 to 20 are taken from it. An immense number of

carefully determined facts regarding the pattern of shore lines, the outline of reefs, and the depths of lagoons are thus recorded. The locations of all the excerpts from the several charts are shown by correspondingly numbered rectangles in Figure 1. The larger rectangles are from chart 2124; the others are from charts 1477 and 1473 of larger scale. Two additional figures, 21 and 22, are from H. O. Chart 2961 on the same scale as B. A. 2124; they show parts of the northern coast of New Guinea lying to the west of the area of Figure 1. A number of figures from these charts are here included because the features under discussion are unusual and because large-scale charts of such features are not generally accessible.

The island of Tagula is 30 nautical miles long from east-southeast to west-northwest—or from east to west, as this slightly oblique trend will be hereafter stated; it is eight or nine miles wide, and has 10 summits from 1330 to 2645 feet in altitude. The island is overlapped on the north by a series of satellite islands, known as the Calvados chain, shown in Figures 10 to 13; the chain begins about seven miles north of the middle of the main island, as shown in Figure 6, and extends 70 miles to the west, with more than a score of members, the largest having a length of 11 miles and a height of 1110 feet. The main island and its satellites are all charted as having irregular and non-clift shores, in which the mountain spurs advance as sloping points and the valleys retreat in open embayments. The shores are in part bordered by fringing reefs up to a mile or more in width. In view of so great a fringing-reef width, it is probable that bay-head deltas have a considerable development, and that but for their presence the shore-line embayments would extend a mile or more inland back of their charted heads, making the island shoreline much more irregular than it is now.

Tagula and its satellite chain are surrrounded by an extraordinary barrier reef of irregular oval outline, having diameters of 112 miles east-west, and 30 miles north-south. The coral seas contain no finer example of an encircling reef. It is strongly developed around the eastern curve of its great circuit (Fig. 5), where the reef flat attains a width of one or two miles, and where it is interrupted by only four passes in a distance of 110 miles. For eight miles along the mid-north coast of Tagula the barrier joins the island shore as a fringe, half a mile wide, as shown in Figures 6 and 17; here a steep descent is made to 200 fathoms or more in a mile from the island shore. North of the eastern end of the Calvados chain, the slightly submerged reef flat is still a formidable barrier, a mile or more in width, as shown in Figures 12 and 13. For a distance of 20 miles in the western part of the southern half of the oval, the reef is charted as a "sunken barrier" at depths of from three to eight fathoms, shown in part in Figure 7.

Fig. 3. Panniet

Around the northwestern part of its circuit the reef is strikingly discontinuous; it there consists in part of small patches, but more commonly of atoll-like loops and rings, 36 in number and from one to five miles in diameter, enclosing little lagoons from 10 to 17 fathoms in depth. Some of the loops are long and narrow; one of this kind stands at the northern turn of the great barrier (Fig. 10); others are pronouncedly crescentic, with the horns pointing into the great lagoon (Fig. 9). The patches, loops and rings are separated by passages from 13 to 35 fathoms deep and from one-quarter to three miles wide, the widest being in the southwestern arc of the reef circuit (Fig. 8). The passages between the crescentic loops are peculiarly long and narrow, like those on either side of the Utian loop (Fig. 9).

Several of the reef loops include small or minute islets, 26 in all, ranging in height from 40 to 530 feet. The largest, Utian (Fig. 9), in the western part of the barrier is 1½ miles across, and 460 feet high; the longest, Sabari (Fig. 12), stands in an imperfect loop where the looping of the reef first begins, northwest of Tagula; it is four miles in length and 180 feet in height. The higher islets have strong slopes, but with very few exceptions they do not appear to be clift. These islets will be here called outposts. As elements of a barrier reef, both the outposts and the reef loops from which they rise are so exceptional as to be almost unique. They have special significance as witnesses regarding the theories of coral-reef formation, and will be considered in detail in later sections.

The great lagoon enclosed by the Tagula barrier reef is divided by the satellite islands of the Calvados chain into a smaller northern and a larger southern compartment. The northern compartment measures about 25 miles east-west by 10 miles across, and occupies about one-sixth of the entire reef-enclosed space, which must approach 2000 square miles in total area. The southern compartment measures about 112 miles east-west by 20 miles across, and occupies about four-sixths of the enclosed space; the remaining sixth is taken by Tagula and the Calvados islands. The greater part of the lagoon floor, at a moderate distance from the outer reef and from the inner islands, is a very gently undulating surface, as a rule from 25 to 38 fathoms in depth; numerous soundings show the bottom to be covered with sand and coral. The lagoon floor rises gradually toward the outer reef and more rapidly toward the inner islands. The greatest depths, 49 fathoms in the central part of northern or smaller compartment (Fig. 10) and 46 fathoms in the southern or larger one, are in both cases much nearer to the dividing island chain than to the surrounding barrier reef. Where the reef is near the enclosed islands, the narrower lagoon is reduced in depth (Figs. 6, 12 and 13). Occasional reef shoals and

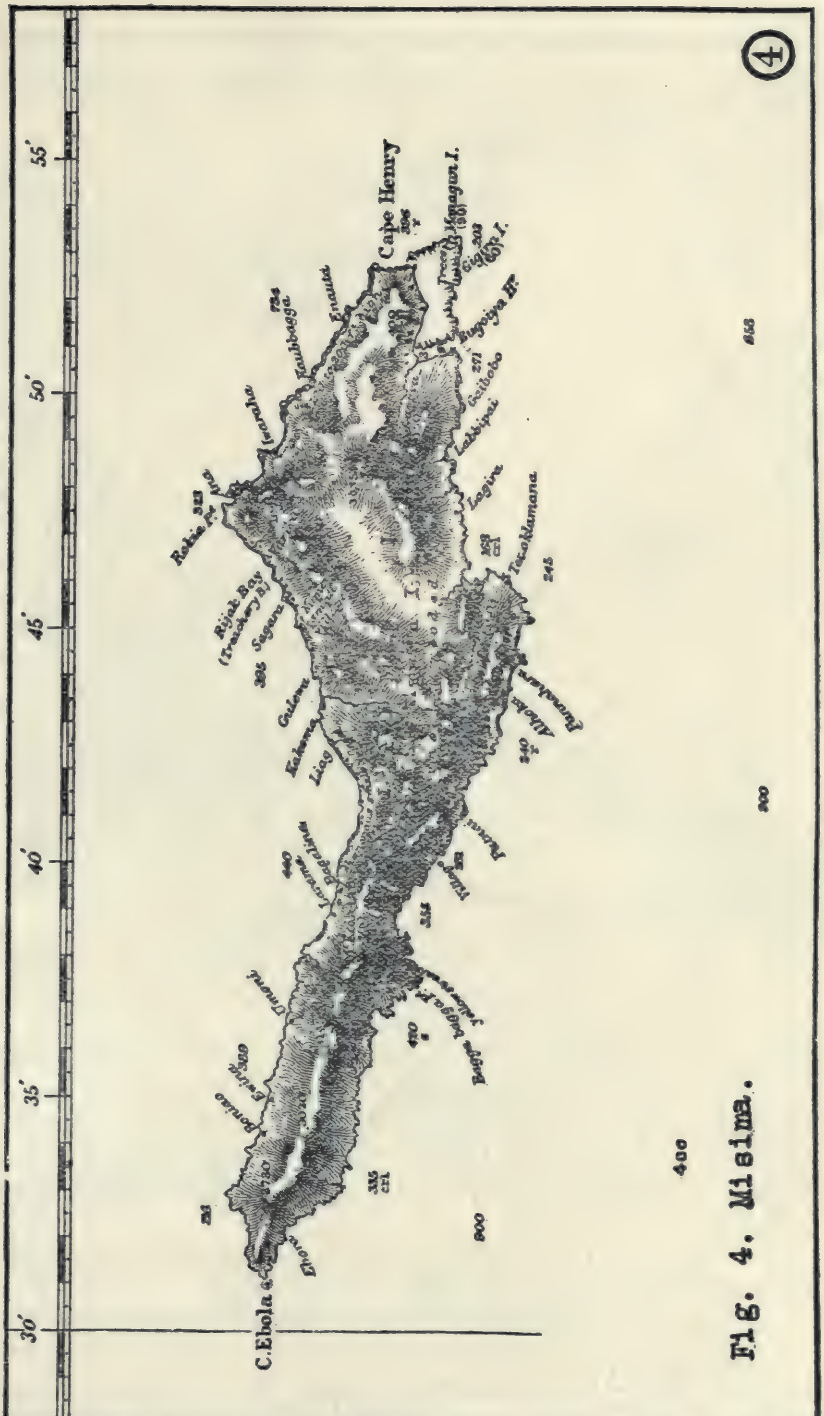

Fig. 4. Misima.

Fig. 5. East End of Tagula Barrier Reef.

patches and a few "lagoon atolls" of small size rise from the lagoon floor. The exterior slope of the barrier reef falls off rapidly into deep water. A few off-shore soundings outside of the barrier show depths of over 600 fathoms two miles from the reef on the northwest and north. Such are the chief facts concerning Tagula presented by the charts.

If the waters of the ocean were removed, Tagula and its satellites would appear as relatively low mountains emerging from the almost level surface of a large and steep-sided plateau, which would stand about 2000 feet above the surrounding bed of the ocean. The barrier reef would form a low rampart around the plateau margin; the rampart would be level, broad, regular, and almost continuous on the south-

Fig. 6. Middle of Tagula.

east, but narrower and irregularly discontinuous on the northwest; and the rampart loops in the northwest, all rising to the same level, would be surmounted by the small outpost islets, a few of which would be twice as high above the rampart as it is above the adjoining surface of the lagoon plateau.

Rocks of Tagula and Its Neighbors.—The few geological observations that have been thus far made in the Louisiade archipelago[1] show that the principal islands are composed for the most part of steeply inclined and greatly eroded schists and slates, trending about east-west, like the similar rocks in the northern ranges of New Guinea; but a few of the Tagula satellites are partly or wholly composed of basalt, and most of the outposts appear to consist of elevated and eroded reef limestone. Gold has been found in no great quantity on some of the islands.

[1] J. Macgillivray. Narrative of the Voyage of H. M. S. Rattlesnake. 2 v. London, 1852. Huxley was the surgeon on this surveying vessel. Mica slate is reported on the northwest coast of Tagula, I, 210, and not far away on Pig Island (Nimea), I, 188; Brierly island (Dadda hai), I, 232, has mica slate and talc and chlorite schists.

B. H. Thompson. New Guinea: Narrative of an Exploring Expedition to the Louisiade and D'Entrecasteaux Islands. Proc. Roy. Geogr. Soc., 1889, 525–542. Tagula, here called "Sudest," was visited at Coral Haven, near the west end of its north coast, and found to consist "of a slaty formation with veins of crystalline quartz running through it in all directions." Joannet, the largest of the Calvados chain, near Tagula, showed "slate with veins of quartz;" Misima, schistose slate and recently uplifted "coral," cut by mountain torrents. The three D'Entrecasteaux islands, Normanby, Ferguson and Goodenough, lying not far north of the eastern end of New Guinea are described as of similar composition with some volcanic rocks. Admiralty Chart 938 shows these islands to be somewhat embayed and not clift; some of the points have very narrow fringing reefs; soundings around them are few.

A. G. Maitland. Geological Observations in British New Guinea. Queensland Geol. Survey, Publication No. 85, 1892. This report includes three large maps with partial geological coloring. The larger Louisiade islands, as far as colored and described, consist chiefly of schist. Basalt occurs in several islands at the western end of the Calvados chain (part of Moturina, and all of Ululina, Venariwa, Panarora) and in 4 near-by outposts (Gulewa, Utian, Pana-roba and Rara). Two other outposts farther southwest (Panasia and Pana-vara-vara) are colored as elevated coral limestone. The composition of most of the islands in the Calvados chain and of most of the smaller outposts is not indicated. Misima is made chiefly of schist with terraces of elevated reefs at various altitudes.

A. G. Maitland. Salient geological features of New Guinea. Journ. W. Austral. Nat. Hist. Soc., II, 1905, 32–56. This paper is chiefly an abstract of the preceding report. Kimuta, the largest of the Renard islands north of Tagula, is a "raised coral reef." The account of Misima island, p. 41, is followed by a paragraph beginning: "On the northern coast," as if referring to this northern island of the Louisiade group; but comparison with the earlier report shows that the northern coast of the eastern part of New Guinea is intended.

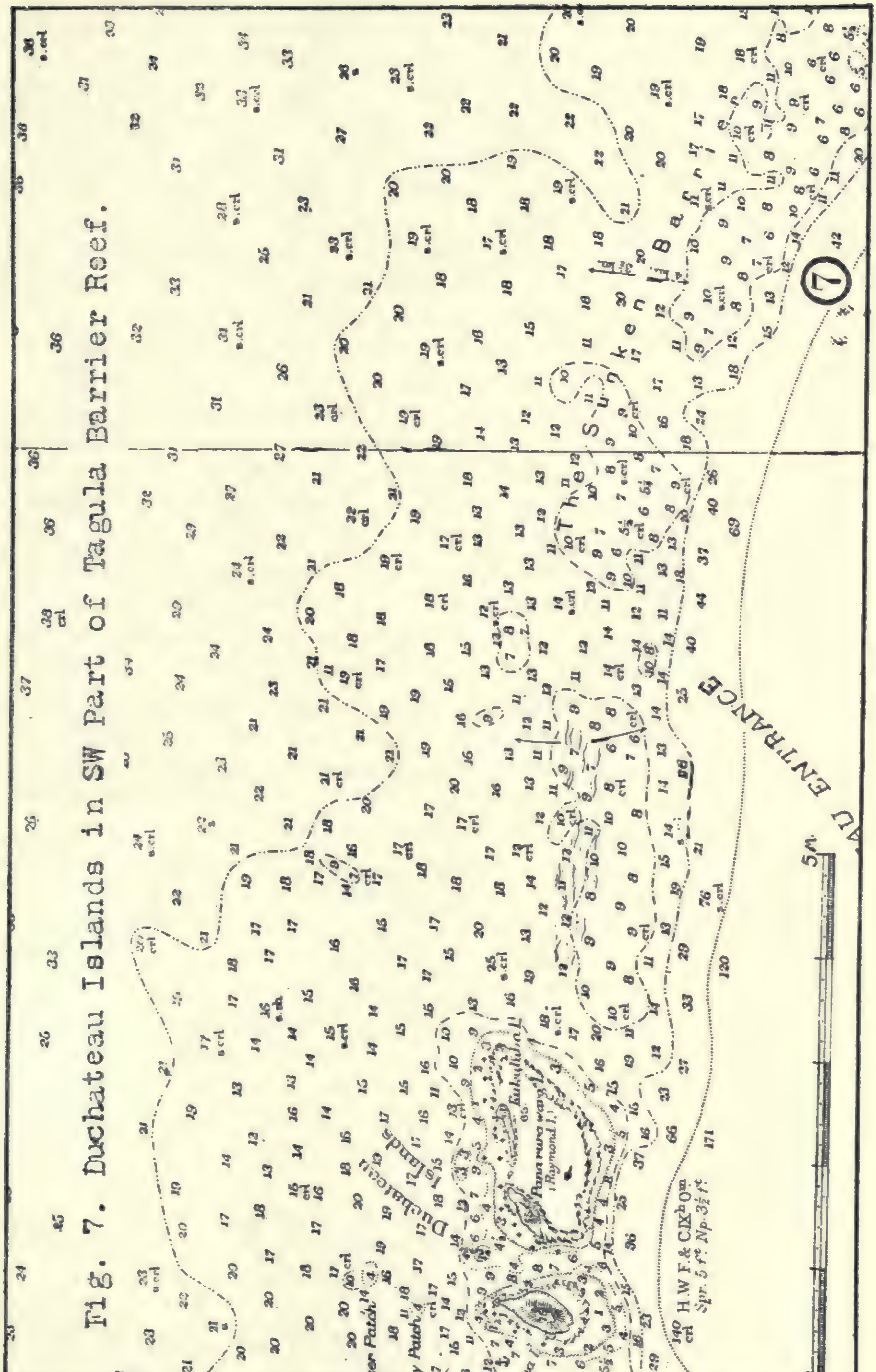

Fig. 7. Duchateau Islands in SW Part of Tagula Barrier Reef.

Inferences Based on Charted and Reported Facts.—Tagula and its satellites, as well as Rossel, Panniet and Misima, appear to be the higher parts of an eastward submarine extension of the mountain ranges of northern New Guinea. The structure, form and trend of the islands and their relation to each other strongly suggest that the portions of the range which they represent had reached a mature or later stage of erosion while the whole region stood higher than now, and that the separation of the archipelago from New Guinea, and of the islands in the archipelago from each other, was brought about by a geologically modern submergence. The fauna of the islands also suggests a recent separation from New Guinea. The amount of pre-submergence erosion appears to be immensely greater than could have been accomplished during the lowered stands of the ocean in the Glacial epochs of the Glacial period; and the depth of submergence indicated by inter-island soundings is many-fold greater than the most liberal estimate of the change of ocean level during the Glacial period. Hence the submergence is presumably due chiefly to a strong subsidence of the region, increasing eastward, in comparison with which the fluctuations of ocean level during the Glacial period were small and short-lived.

It is, however, also conceivable that the larger islands and the Calvados chain represent faulted crustal blocks, instead of the higher parts of a continuous range; but even if so, the several blocks must for a time have stood much higher than now in order to be eroded to their present form before they were submerged to their present attitude; for as far as can be inferred from the dimensions of the island valleys and of the valley embayments, the erosion is, as already noted, too great in amount, and appears to be continued too far below present sea level, to have been accomplished during the lowered stands of the ocean in the Glacial period. Hence it may be concluded that, even if the islands represent fault blocks, their present form, including their submarine slopes to a considerable depth, could not have been sculptured during the lowered stands of the Glacial ocean, and their present depth of submergence could not have been caused by the rise of the ocean in Postglacial time. Whether the islands are the unfaulted crests of a long mountain chain or the crests of a series of blocks in a faulted range, they point to a pronounced subsidence of the deformed and eroded mountain belt in geologically modern time.

The instability of the region is further indicated by certain differential movements, modern in date and of no small amount, of which the contrasts between Misima and the other islands of the group, and between the northern and southern coasts of eastern New Guinea give striking evidence. Tagula and its larger satellites, as well as Rossel, are not described as having elevated reefs on their flanks, but are sur-

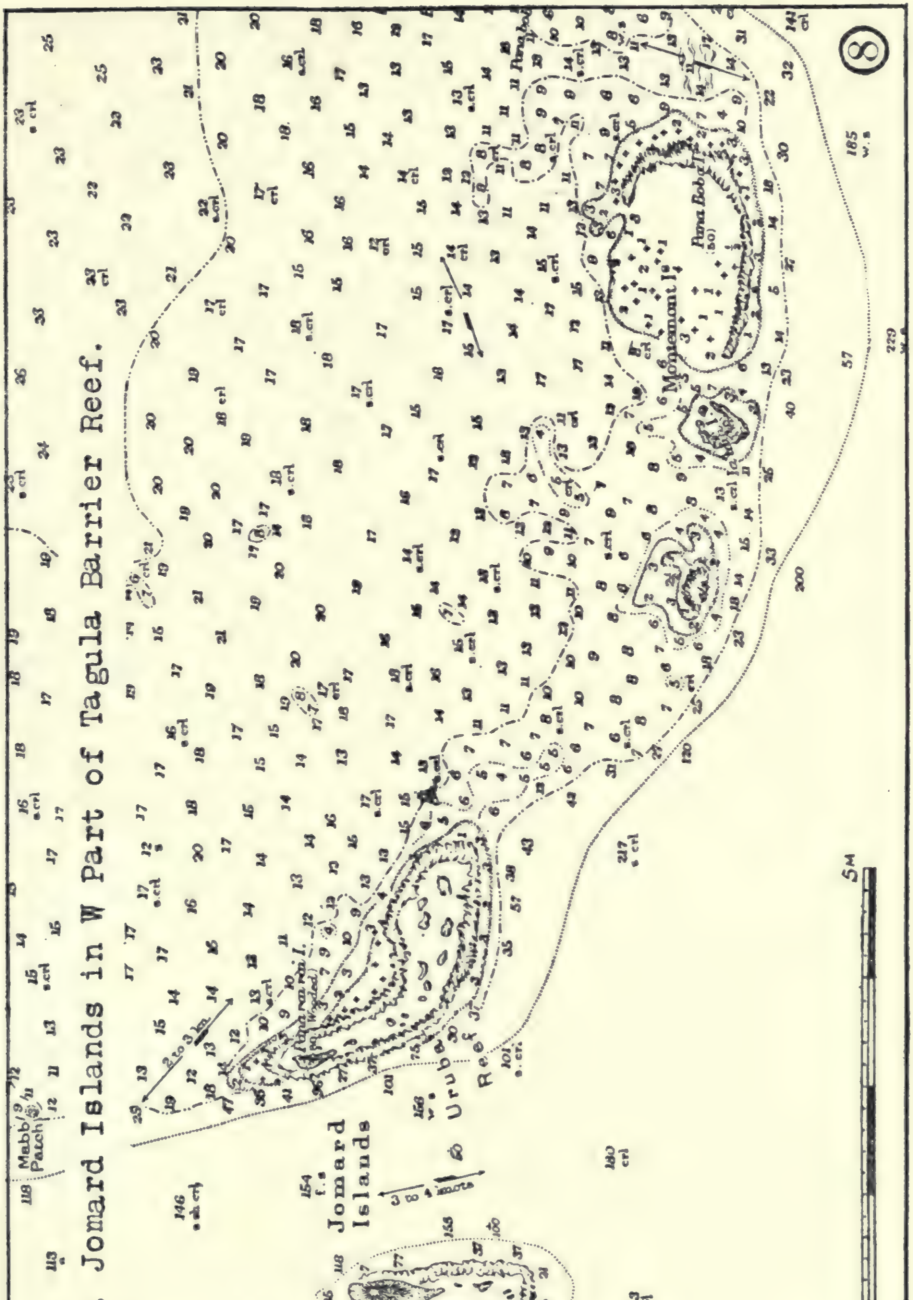

Fig. 8. Jomard Islands in W Part of Tagula Barrier Reef.

rounded by great barrier reefs and lagoon floors at and a little below present sea level; yet that some of the Tagula satellites bear remnants of elevated reefs will be suggested below. A little farther north, Panniet, 1500 feet in height, and its small companion, Panapompom, are likewise associated with a sea-level barrier reef as in Figure 3; but here an elevated reef, 10 feet above sea level, is said to occur on the north side of the lagoon. Maitland is quoted as reporting that "reefs raised only a few feet above the sea level, such as those of Pannietta, present along the shore white perpendicular cliffs of varying height, above which is an almost level tableland, very broken and rugged, and with a very uneven surface."[2] Panniet is peculiar in having no reefs on its northern side, where it is charted (Fig. 3) as having cliffs which descend into deep water; these cliffs appear to be much higher than the "few feet" of the reef cliffs reported in the lagoon by Maitland.

Still farther north, Misima (Figs. 4, 14 and 15) presents very different features. This island, measuring 22 by 10 miles and rising 3500 feet, slopes rapidly into deep water and, except at its southeastern point, has no sea-level reefs; but it is according to Maitland terraced by elevated reefs to considerable altitudes above sea level, and some of the reefs were found to rest unconformably on the eroded schists of the island slope. This observer reports that the "elevated reef masses [of Misima] when viewed from a distance, presented the appearance of vertical walls and almost horizontal terraces, stretching often for considerable distances. The faces of these cliffs are sometimes covered with vegetation to such an extent as to present the appearance of huge walls of foliage. The thickness of these reef masses I had no opportunity of ascertaining; it is, however, improbable from their mode of occurrence that their vertical thickness can be very great."

The southern coast of eastern New Guinea is, like Tagula, fronted by a long barrier reef. The northern coast (Figs. 21, 22) descends rapidly into moderately deep water and is bordered only by narrow and discontinuous fringing reefs at present sea level; and at certain points it has, again according to Maitland, coral limestones remarkably well preserved and resting unconformably on the older rocks at various levels up to altitudes of 2000 feet.

On Misima the unconformity of the elevated reef limestones on their foundations proves a submergence before the recent emergence;

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[2] Jack and Etheridge. Geology and Paleontology of Queensland and New Guinea, London, 1892; see p. 685.

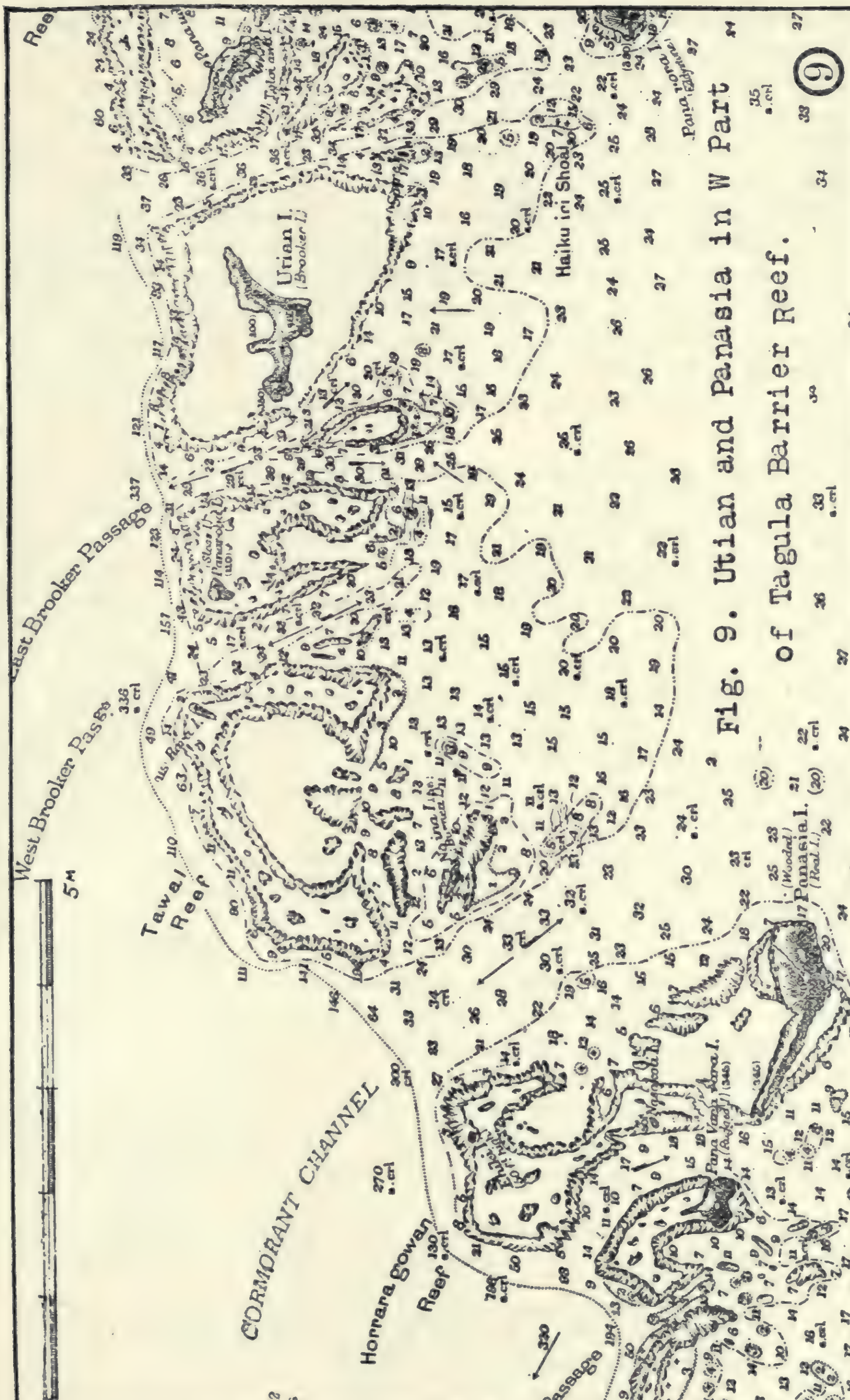

Fig. 9. Utian and Panasia in W Part of Tagula Barrier Reef.

and the submergence must be estimated as greater than the emergence, because the eroded slopes of the land descend below present sea level.* This is well shown by the embayed shore line of Misima, especially its western part, as in Figure 14. It is probable that, but for the reef terraces of this island, some of which lie near present sea level, its shore line would be decidedly more irregular than it now is. Whether the elevated reefs were made during pauses in an intermittent submergence before a rapid emergence, or whether a rapid submergence was followed by an intermittent emergence, with reef building during its pauses, or whether some of the reefs were formed during pauses in submergence and some during pauses in emergence cannot now be determined; but there can be no question that the submergence of Misima, presumably caused by subsidence, was at times more rapid than the rate of reef upgrowth.

Similar inferences are supported by the features of eastern New Guinea along its northern coast. Its easternmost end is itself embayed, and is continued by several elaborately embayed islands, which are shown on Hydrographic Office Chart 2950 and of which as well as of the northern coast for some distance westward, a general description is given by Moresby, a recent and yet the first explorer of that region.[3] There are parts of the northern coast here shown in Figures 21 and 22, where, as around Misima, sea-level reefs are imperfectly developed or wanting. The second of these figures, including the great volcanic mountain of Trafalgar with its beautifully embayed shore line, is particularly striking. This dissected volcanic mountain resembles that of Banks peninsula on the eastern coast of South Island, New Zealand, except that the latter being outside of the coral seas, was strongly clift by the sea while it was dissected by radial consequent streams; but Trafalgar, which Moresby says descends " to the sea in open grassy and wooded slopes," appears to have been protected from abrasion, probably by coral reefs as it is inside the coral seas, while it was suffering dissection. The cliffs of Banks peninsula are still in part visible, in spite of the embayment of its valleys. If cliffs had been cut around the base of Trafalgar while its valleys were eroded, they might be seen today as plunging cliffs now that the valleys have been embayed. The scanty information in hand about this region does not suffice to determine the relation of the general erosion of the mountain slope on which the ele-

* The importance of unconformable reefs is pointed out in one of my essays: The Geological aspects of the coral-reef problem. Science Progress, XIII, 1919, 420–444.

[3] J. Moresby. Recent Discoveries in the southeastern part of New Guinea. Proc. Roy. Geogr. Soc., XVIII, 1873, 22-31. See also, "Discoveries and Surveys in New Guinea," by the same author (*London*, 1876)

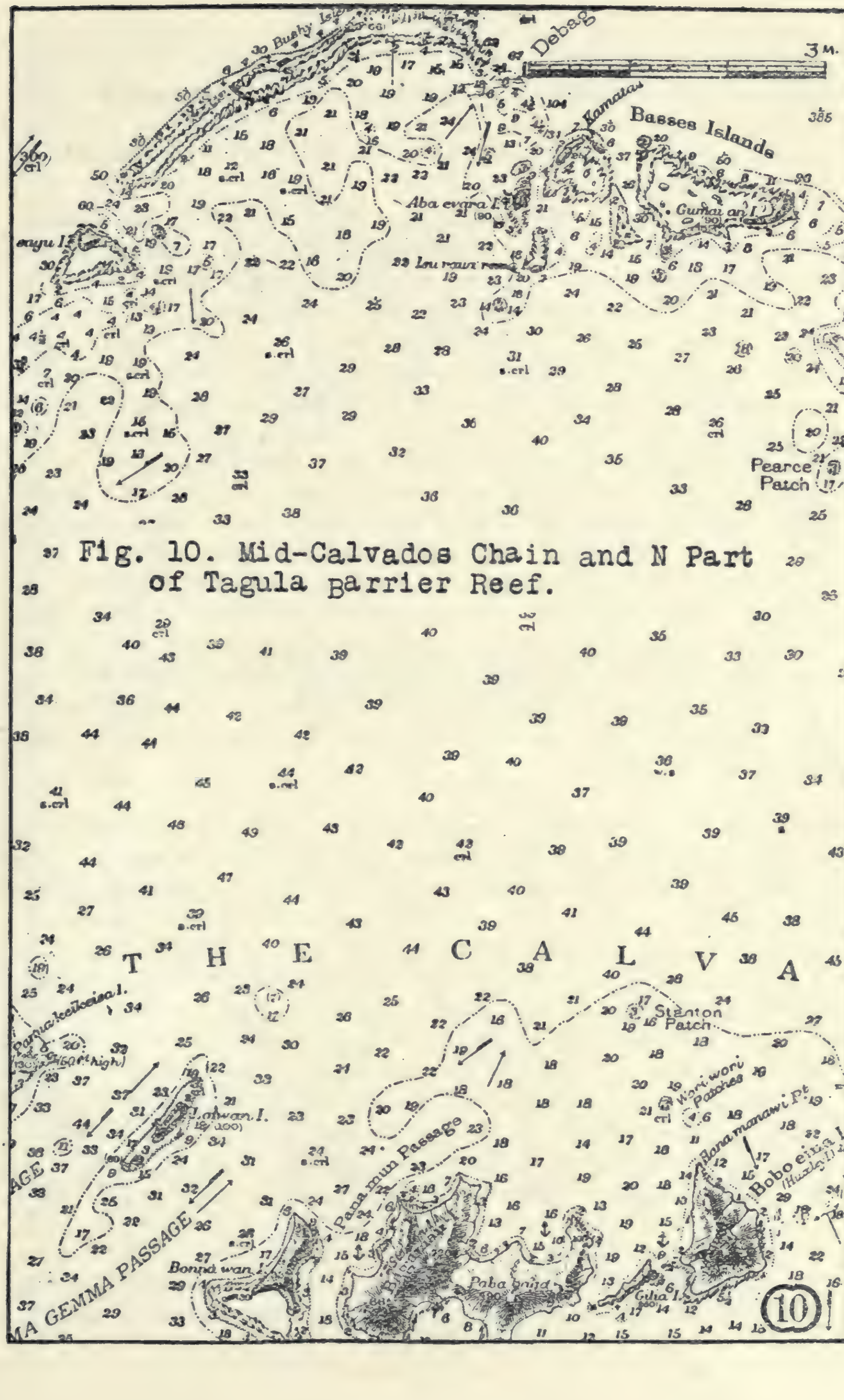

Fig. 10. Mid-Calvados Chain and N Part of Tagula Barrier Reef.

vated unconformable coral reefs rest, as reported by Maitland, to the erosion of Mt. Trafalgar; nor the relation of the changes of level shown by the elevated reefs to the changes of level shown by the present embayed shore line; but in any case the coast must be regarded as markedly unstable, and as having experienced strong differential movements in very late geological time.

Smaller differential movements, possibly of earlier date, as explained below, are indicated by the elevated coral limestones reported on certain outpost islets and inferred on others around the northwestern part of the Tagula barrier. Very recent movements are suggested by the "sunken barriers" or submerged reefs, examples of which are found not only in the southwestern part of the Tagula barrier (Fig. 7), as already stated, but again and on a much larger scale along the southern side of New Guinea. There, in a total length of 380 miles, the barrier reef, as represented on British Admiralty Charts 2122, 2123, is submerged for two stretches of about 60 and 140 miles; the imperfectly enclosed lagoon varies from five to 20 miles in width; back of the longer stretch of the submerged barrier the lagoon, which is ordinarily 20 or 30 fathoms deep, has the unusual depths of from 45 to 59 fathoms. In view of the successful growth of sea-level barrier reefs elsewhere in this region, these "sunken barriers" appear to be better explained by local and gentle down-warping of pre-existent sea-level reefs at a rapid rate and a very recent date, than by a local failure of reef upgrowth from a stable foundation. They may in time be built up to sea level again.

Relation of Crustal Instability to Reef Formation.—In consideration of these various facts and inferences, it may be concluded, with much probability of correctness, that long after the strong deformation by which the rocks of the region were given their steep inclination with eastward trends, and not until the attainment of an advanced stage in the great erosion which began with but long outlasted the strong deformation, the Louisiade extension of eastern New Guinea suffered a pronounced subsidence or down-warping, increasing eastward; and that at a still later date the northern border (Misima) and the western part (eastern New Guinea) of the region suffered an upheaval or up-warping of less amount. This conclusion, which has been reached by inferences that are independent of all coral-reef theories, seems to make it necessary to explain the great submarine body of the sea-level barrier reefs in the Louisiade by upgrowth during the progress of the subsidence. The great submarine mass of the barrier reef of Tagula, with which we are here particularly concerned, should therefore be regarded as having grown up during the long continued

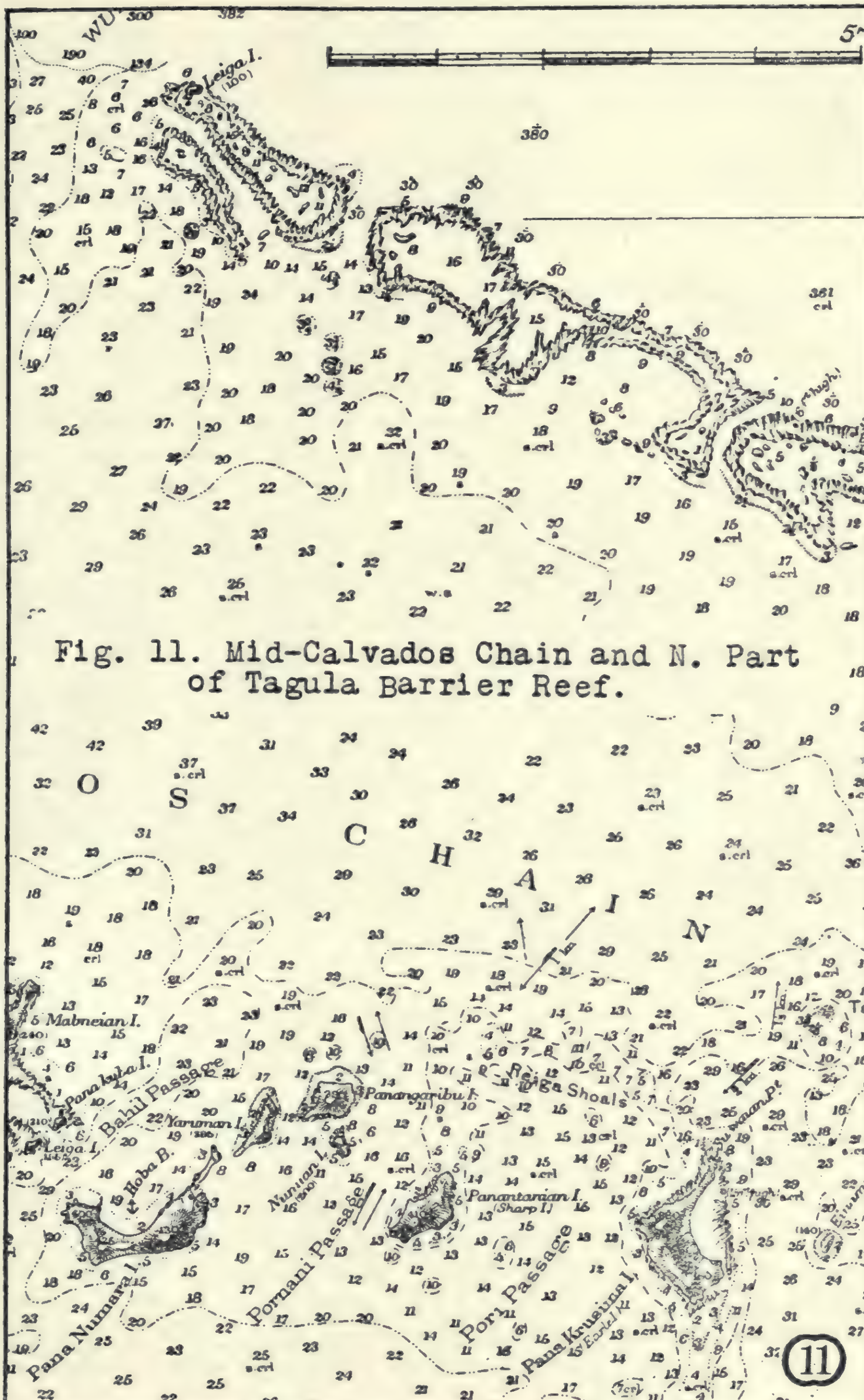

Fig. 11. Mid-Calvados Chain and N. Part of Tagula Barrier Reef.

and probably intermittent subsidence of its original foundation, which now lies at an unknown depth; and during such subsidence the enclosed lagoon floor should be conceived as having been progressively aggraded with sediments of unknown thickness, essentially according to Darwin's theory, whatever subordinate changes recently took place during temporary movements of upheaval and during the fluctuations of sea level in the Glacial period. Those changes will further be inquired into in later paragraphs.

Suggested Origin of Outpost Islets and Reef Loops.—Both of the singular features by which the northwestern half of the Tagula barrier reef is so strikingly characterized are encountered rarely, if at all, elsewhere in the coral seas. Their intimate association here suggests that they are causally connected. The reef loops cannot have produced the outposts, but the outposts may have, under certain relatively simple conditions, determined the formation of the reef loops, and the manner of that determination will be here inquired into.

Two of the larger outposts, Gulewa and Utian, at the western end of the Calvados chain, are described by Maitland as composed of volcanic rocks, like other western Calvados islands. In two small outposts, Pana-roba and Rara, west of Utian (Fig. 9), Maitland says "basalt occurs;" and Panasia, rising 530 feet, the highest of all the outposts, and its neighbor, Pana-vara-vara, 345 feet high, are colored on his geological map as consisting of "elevated coral limestone." The other outposts, a score in number, are of unknown composition, mostly of very small size, and from 40 to 120 feet in height. It is not likely that the majority of them are made of volcanic rocks like Utian, or of schists like Tagula and its larger satellites, because the intimate association of volcanic or of schist islets with the loops of the great barrier reef would be difficult to explain without the adoption of utterly improbable assumptions. On the other hand, if the outposts are regarded as for the most part residuals of a former barrier reef, here uplifted and much eroded and then partly submerged, their explanation offers no difficulty, in whatever way the preexisting barrier reef was formed. This view as to the origin of the small outposts and of the reef loops within which they rise is therefore provisionally adopted, and will now be stated more fully.

Let it be imagined that the northwestern part of the Tagula barrier-reef region was uplifted not long ago geologically 300 or 400 feet, while the southeastern part remained about stationary. The uplifted part will have been protected from wave attack by the downward migration of living fringing reefs on its emerging slopes; while its emerged part will have been gradually reduced, chiefly by solvent erosion, to

Fig. 12. East Part, Calvados Chain and Adjoining Barrier Reef.

residual masses of irregular form. When the erosion is well advanced, let a subsidence of 200 or 300 feet take place at such a rate that the fringing reefs will grow up as small barrier-reef loops around each of the residual summits of the eroded barrier. If the ocean suffered a Glacial lowering of level while the reef was elevated and a Glacial rise of level when the elevated reef subsided, the changes due first to erosion and then to reef-loop upgrowth would be emphasized. Each low summit that is completely submerged will be replaced by a little atoll loop; each higher summit, still visible today as an islet, will be surrounded by a little barrier-reef loop of similar outline. Most of the loops will be elongated in sympathy with the curve of the former barrier reef. The surviving islets will resemble, except for being smaller, the much eroded limestone islands now enclosed by the barrier reefs of southeastern Fiji, as figured by Agassiz.[4] Thus the peculiar features of the Tagula barrier reef may be explained.

Reasonable as this explanation may seem, it should not be adopted definitely until the composition of the outpost islets is determined by direct observation. But in the meantime some additional consequences of the explanation may be noted. First, if the northwestern half of the former barrier were moderately uplifted, the islands of the Calvados chain should have suffered a similar uplift; and for a while thereafter they should have been benched with emerged fringing reefs; but after a time long enough for the advanced erosion of the main barrier reef, the fringing reef benches should be largely or wholly destroyed, thus revealing the maturely eroded underlying slopes of the schist islands more or less completely. Then after subsidence, an island on which steep-sloping remnants of the emerged reef were still clinging might have steep spur ends. This is warranted by the forms of Vanua Mbalavu in eastern Fiji, an island that is believed to have suffered essentially the same series of changes of level that are here assumed for the great Tagula barrier. It has the sloping spurs of a maturely eroded volcanic island on one side, and on the other the precipitous cliffs of a greatly dissected body of limestone which must have formerly wrapped around the entire island. Some of the Calvados islands have precipitous spur ends, as will be shown below. It is therefore possible that they may have been formed as here proposed. But as above noted, no decision on this point should be announced in advance of detailed observations as to the composition of the islands.

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[4] A. Agassiz. The Fiji islands and coral reefs. Bull. Mus, Comp. Zool., XXXIII, 1899, 1–167; see plates 83, 90, 94.

W. M. Davis. The origin of certain Fiji atolls. Proc. Nat. Acad. Sci., II, 1916, 471–475.

Fig. 13. East Part, Calvados Chain and Adjoining Barrier Reef.

Second, the assumed elevation of 300 or 400 feet may have laid bare the northwestern part of the Tagula lagoon floor as a gently sloping limestone plain, which would thereupon be subjected to erosion. If, as above suggested, the Glacial lowering of ocean level took place while the reef and the adjoining part of the lagoon floor were elevated, the lagoon-floor plain might have been eroded with respect to a baselevel some 30 fathoms below normal ocean level. When the barrier reef had been eroded so far that its summits were reduced to the form of the present outpost islets, the lagoon-floor might have been worn down to a plain nearly as low as the lowered ocean. If a subsidence of 20 or 25 fathoms then took place and was associated with, or followed by, the rise of the ocean to normal level, the worn-down lagoon-floor plain would be submerged to a depth of 50 or 60 fathoms; but aggradation of the submerged plain by inwashed and local detritus would give the present lagoon floor its actual depth of from 30 to 45 fathoms.

Third, emergence and submergence caused by changes of ocean level will not alone suffice to account for the features of the Tagula barrier reef; because in that case many other barrier reefs should have similar outpost islets enclosed in little reef loops, and such is not the case. A moderate elevation and a smaller subsidence of the northwestern part of the Tagula region, associated with Glacial changes of ocean level, give a better explanation of the facts.

Fig. 14. West End of Misima.

Fourth, while the changes were taking place in the northwestern part of the Tagula barrier, the reefs in the more nearly stationary southeastern part should increase in breadth. This inference is well sup-

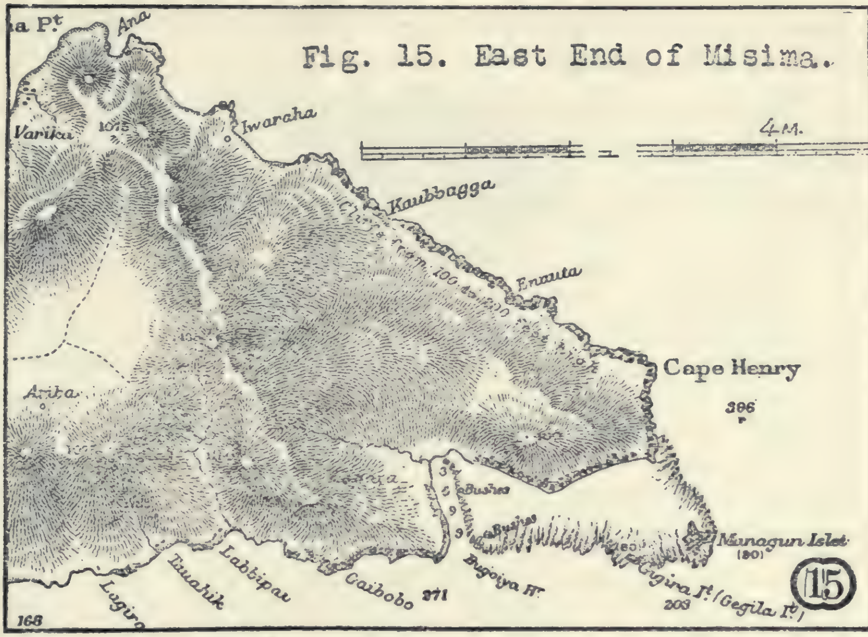

Fig. 15. East End of Misima.

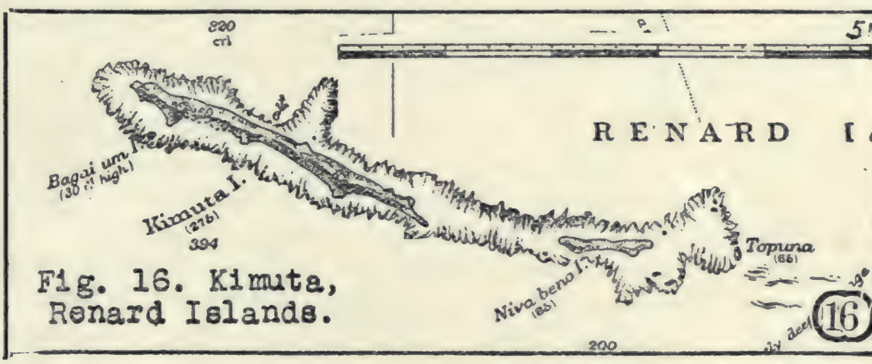

Fig. 16. Kimuta, Renard Islands.

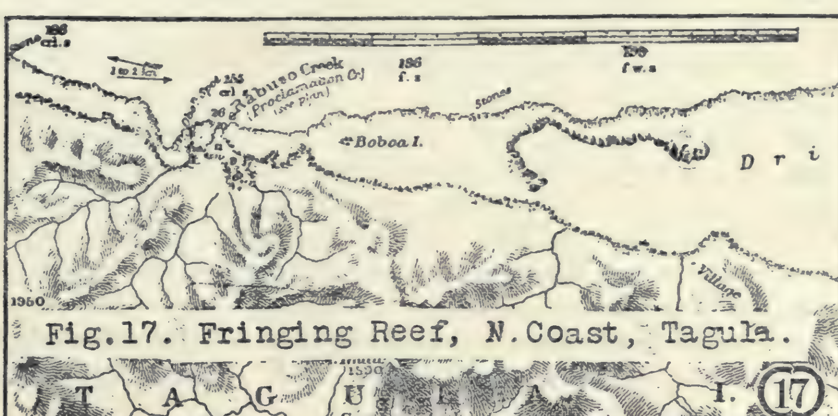

Fig.17. Fringing Reef, N.Coast, Tagula.

ported by the facts, as here represented in figures of the islands and reefs.

Fifth, if the northwestern part of the Tagula barrier reef has been thus uplifted, eroded, and submerged, similar changes might be expected to have taken place on some of the neighboring islands, and these changes should be there also recorded by the occurrence of outpost islets in their reefs. An examination of the charts reveals truly enough several minute outpost islets in the Rossel reef; Figure 18 shows Tree islet, 40 feet high; Figure 19 shows Heron islet, 30 feet high; and Figure 20, Adele islet, 130 feet high: the situation of the last outpost at the eastern extremity of the Rossel barrier is certainly very exceptional. The eastern end of Misima (Fig. 15) is peculiar in being bordered by a mile-wide fringing reef; and two outpost islands rise from it; Managan islet, 90 feet, and Gegila islet, 80 feet; the probability that these outposts islets are composed of elevated reef rock is increased by the reported occurrence of elevated reefs on Misima.

The southeastern part of the Panniet barrier reef, which approaches the northern turn of the Tagula barrier, has a small outpost islet (Fig. 3), 80 feet high; and a detached triangular reef of small size between the two barriers not shown in the figures, has an islet marked "trees 90 feet high." Kimuta, the largest of the Renard islands which lie southeast of Misima, is shown (Fig. 16) to be a slender ridge, three miles long, one-quarter mile wide, and 275 feet high; it is described by Maitland as a "raised coral reef." Near by is the smaller Nivabeno island, 85 feet high; also two minute outposts, 30 and 65 feet high. The resemblance of Kimuta to Sabari, the largest of the Tagula outposts (Fig. 12) is very striking. Sabari is a mile longer than Kimuta, about twice as wide and half as high; and, like Kimuta, it is associated with minute neighboring islets. Finally, the western of the two Jomard islands (Fig. 8) with its reef loop two miles long and its outpost islet 85 feet high, although separated from the Tagula barrier by a water passage two miles wide and over 150 fathoms deep, closely resembles the eastern of the two islands, which makes part of the Tagula barrier, with its reef loop three miles long and its somewhat smaller outpost 80 feet high. None of these outpost islets, except the western Jomard, are enclosed in reef loops like those of the Tagula barrier; they rise from broad reef flats. Otherwise they are very similar to the Tagula outposts. Hence as above stated the proposed explanation of the Tagula outposts by an episode of elevation, erosion and subsidence is provisionally adopted. Similar episodes may have characterized earlier stages of the great subsidence.

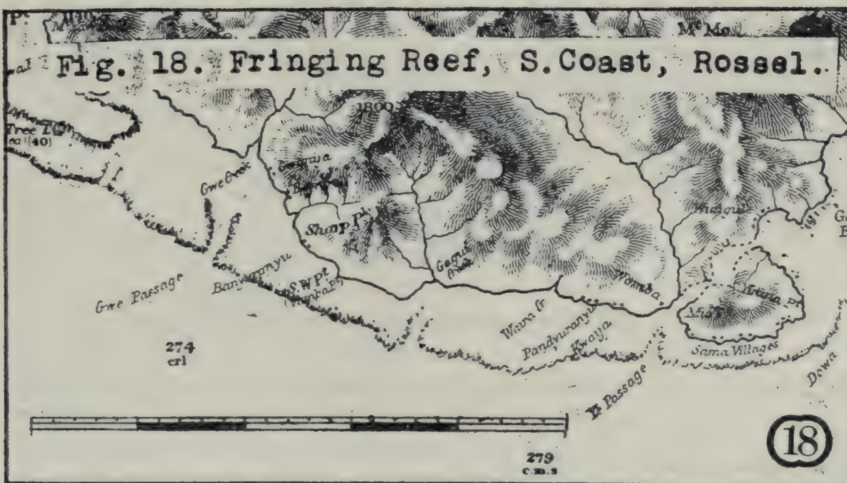

Fig. 18. Fringing Reef, S.Coast, Rossel.

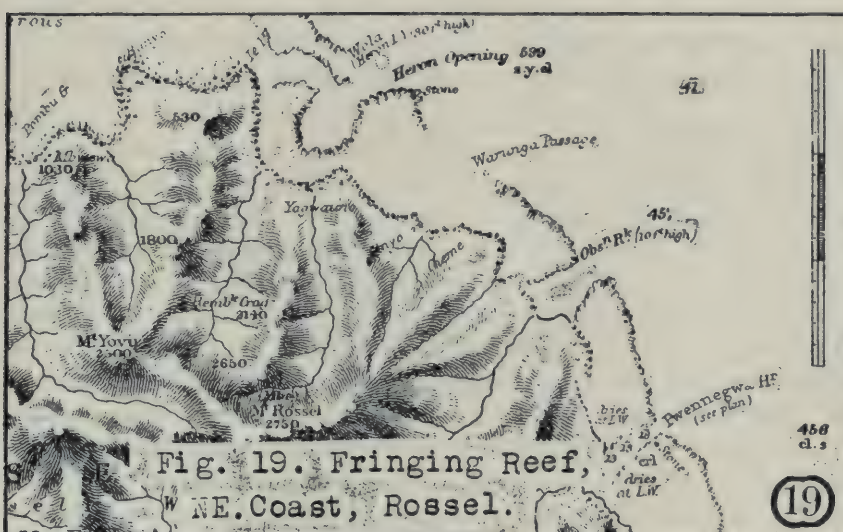

Fig. 19. Fringing Reef, NE.Coast, Rossel.

Abrasional Theories of Coral Reefs.—The charts of the Louisiade islands are particularly instructive because of the evidence, to be detailed below, which they afford against the validity of certain coral-reef theories in which abrasion plays a leading part. It has been urged by the proponents of these theories that the prevailing flatness of lagoon floors cannot be explained by the distribution of aggrading sediments in great thickness on subsiding foundations of uneven form, so well as by their distribution in small thickness on nearly level platforms abraded at a standard depth around stationary islands. One such the-

ory was announced some 30 years ago by Wharton, but it gave no reason for the absence of defending reefs while abrasion was in progress; the theory nevertheless tacitly postulated their absence and implied furthermore that the abrasion to at least as great a depth as that of lagoon floors was accomplished while the ocean and the islands held their present relative levels. In view of the depths of 30 fathoms commonly found in reef-enclosed lagoons, and of over 40 fathoms found in both compartments of the Tagula lagoon, this theory seems inadequate.

Another abrasional theory recently advanced by Daly[5] is much better argued, in that it assumes abrasion to have taken place while reef-forming organisms were weakened or killed by the chilling of the ocean during the Glacial epochs of the Glacial period, and in that it accounts for the roughly accordant depths and smooth floors of barrier-reef and atoll lagoons by assuming that sub-lagoon platforms were abraded while the chilled Glacial ocean was lowered 30 fathoms or more beneath its normal level. It is especially because of the evidence that the Tagula reef system affords regarding the postulates and processes of this so-called Glacial-control theory of coral reefs that it is here examined.

The examination has already led to the belief that the Louisiade region is characterized by instability which, as the Glacial-control theory recognizes, is prevalent in the southwestern Pacific, and that Tagula in particular appears to have suffered strong subsidence. It may now be added that, in spite of this subsidence, the large lagoon has a depth that accords very well with the depth of large reef-encircled lagoons in the central Pacific region which is assumed in the Glacial-control theory to be of long-continued stability. Hence it may be concluded that, contrary to the argument of that theory, the stability of reef foundations does not seem to be essential for the production of lagoons with accordant depths. A further examination, detailed below, leads to the belief that no significant amount of abrasion was accomplished around Tagula by the chilled waters of the lowered Glacial ocean; therefore the smooth floor of the great lagoon should not be

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[5] R. A. Daly. Pleistocene glaciation and the coral reef problem. Amer. Journ. Sci., XXX, 1910, 297-308.

— — The Glacial-control theory of coral reefs. Proc. Amer. Acad. Arts and Sci., LI, 1915, 157–251.

— — Problems of Pacific islands. Amer. Journ. Sci., XLI, 1916, 153–186.

— — A new test of the subsidence theory of coral reefs. Proc. Nat. Acad. Sci., II, 1916, 664–670.

— — Origin of living coral reefs. Scientia, XXII, 1917.

— — The coral-reef zone during and after the Glacial period. Amer. Journ. Sci., XLVIII, 1919, 136–159.

regarded as the result of relatively moderate Postglacial aggradation on a stationary abraded platform, but as chiefly the result of long-continued and heavy aggradation on an uneven and slowly subsiding foundation of whatever form, as is assumed in Darwin's theory. If this great lagoon has gained a smooth floor at a normal depth in spite of long-continued subsidence, complicated by recent elevation and without the aid of abrasion, it may be further concluded that the abrasion of flat platforms on supposedly stationary islands in the central Pacific, as assumed in the Glacial-control theory, is not essential for the production of smooth lagoon floors of accordant depths. I have elsewhere shown that a number of elevated and eroded limestone islands in Fiji, believed to have originated as atolls, show no abraded volcanic platforms.[6]

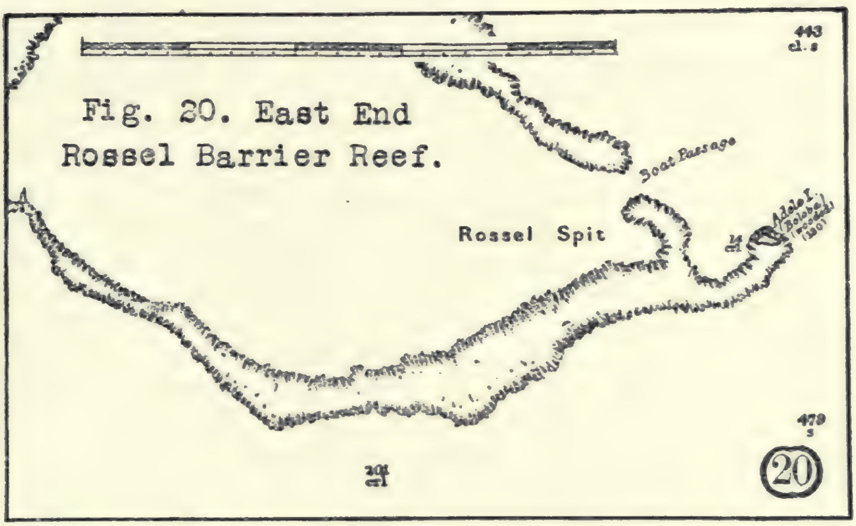

Fig. 20. East End Rossel Barrier Reef.

It may be that, in view of the situation of the Tagula reef, the advocates of the Glacial-control theory would regard its corals as having survived the small lowering of ocean temperature there occurring in the Glacial Period, and would not insist that its lagoon floor is underlaid by a platform of abrasion; but if such opinions were accepted, the resemblance of the Tagula reef to other barrier reefs and of its lagoon floor to other lagoon floors where abrasion is assumed to have acted, would be embarrassing: for the resemblance would suggest that, if inhibition of coral growth and abrasion of pre-existent reefs did not take place around Tagula, they surely need not be appealed to in the preparation of other reefs and lagoons. It will therefore be supposed

[6] The structure of high-standing atolls. Proc. Nat. Acad. Sci., III, 1917, 473-479.

here that the advocates of the Glacial-control theory would regard the Tagula reef as having been formed in the same manner as that adopted by them for the great majority of reefs in the coral seas.

Accordant Depths of Reef-Encircled Lagoons.—The tables of lagoon depths published by Daly—in which the Tagula lagoon was not included—show a certain measure of accordance. The larger lagoons have average maximum depths of from 30 to 45 fathoms; the smaller ones, from 15 to 25 fathoms. It is inferred thereupon that no such accordance should be found " if subsidence has been the essential control in forming coral reefs," and this inference is taken to support the thesis that " most of the reef platforms . . . have such forms, dimensions, and relations to the sea level that they appear to have originated during a long period of very nearly perfect stability for the general ocean floor."[7] Several other considerations may be here adduced. First, large lagoons should as a rule be deeper than small ones, by whatever process their encircling reefs have been formed, because the inwashed detritus from each linear foot of exterior reef face has to aid in the aggradation of a larger sector-area in a large lagoon floor than in a small one. Indeed, as large lagoons are deeper than small ones, it may be fairly stated as a corollary of this principle that a significant share of the detrital material by which lagoons are aggraded must have been supplied by overwash from the exterior of the reef, just as various observers have inferred to be the case in view of the composition of the lagoon sediments and of the inward slope found in many lagoon floors behind their reefs. As far as the detritus consists of organic material formed in the lagoon, its total volume may be regarded as increasing with the lagoon area and as therefore not tending to make small lagoons shallower than large ones. Second, the departures of the depths of individual lagoons from the average depth of other lagoons similar in size is relatively large; and this appears to be better explained by the theory of upgrowing reefs on irregularly subsiding foundations than by the theory of upgrowing reefs on the margins of platforms abraded to a nearly constant depth around stationary islands.

Third, and more important still, Daly's tables do not separate the lagoons in the central Pacific region of assumed " nearly perfect stability " from those in the southwestern region of admitted instability. When this separation is made, it appears that the average values gained from the tables are little changed. It would therefore seem fair to infer that, if reef-encircled lagoons in a region of demonstrated instability

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[7] R. A. Daly. The Glacial-control theory of coral reefs. Proc. Amer. Acad. Arts and Sci., LI, 1915, 157–251; see pp. 194, 162.

usually accord in depth with the lagoons of similar size in a region of assumed stability, the assumption of stability for the second region is rendered improbable, to say the least. The Louisiade lagoons serve to confirm this inference. They are in a region of pronounced instability, and yet have smooth floors, and their depths are accordant with those of similar-sized lagoons elsewhere. The island of Tagula appears to have suffered strong and long-continued subsidence, recently complicated by a small upheaval; yet its great lagoon has maximum depths similar to, but somewhat less than, those of the lagoon of Truk, an almost-atoll in the Caroline group, about 35 miles in diameter, one of the largest reefs of its kind in the central Pacific. Although this lagoon had few soundings of more than 30 or 35 fathoms according to the earlier charts, it has depths as great as 56 fathoms according to later German surveys, and such depths are not much greater than the depth of 46 and 49 fathoms in the Tagula lagoon.

On the other hand, the smaller lagoons in the Louisiade region have smaller depths; witness the Rossel lagoon (Fig. 2), seven miles wide and 39 fathoms deep; the Panniet lagoon (Fig. 3), of similar width and 21 fathoms deep; also the narrower parts of the Tagula lagoon, from five to seven miles wide south of the island (Fig. 6), and 30 or 40 fathoms deep; also, north of the Calvados chain (Figs. 12 and 13), two to four miles wide and 16 fathoms deep. Certain atolls shown to the west of the Tagula barrier (Fig. 1) are of interest here: Bramble haven, 10 miles in diameter, is 20 fathoms deep; Long atoll, 5 by 18 miles, next to the west, has no soundings on H. O. Chart 2942; to the north, Conflict atoll, 5 by 12 miles, is 17 fathoms deep. In other words, the rule established by Daly's tables for the open Pacific of unknown crustal behavior holds good also for the Louisiade region of unquestionable instability. The large lagoons of this unstable region are 40 or 50 fathoms deep; the small lagoons are 20 or 30 fathoms deep. In view of these general considerations, it may be repeated that a long-continued stability of reef foundations is not a necessity for the production of lagoons with smooth floors and roughly accordant depths. Rough accordance of depths obtains even when lagoons in a region of instability are included, and therefore the postulated stability of the central Pacific is not proved by such accordance.

Moreover, it is not to be overlooked that certain lagoons in various parts of the Pacific are in part at least unusually deep, as if their foundations had been characterized by exceptionally active and recent subsidence. Thus Viti Levu, the largest island of the Fiji group, which is believed on independent evidence to have suffered a modern tilting to the northwest, has an extensive and imperfectly enclosed lagoon floor or submarine bank on the northwest side, with depths increasing gradu-

ally to 58 fathoms near the end of the partly submerged barrier reef, and with two soundings of 80 fathoms farther off shore where no reef has grown up. Again, the great lagoon of the Exploring Isles in eastern Fiji, where independent evidence of recent eastward tilting is found, has depths increasing eastward to 70 and 80 or more fathoms. Two soundings of 50 fathoms on the narrow Thikombia bank in northeastern Fiji also deserve mention, for such depths are exceptional on small banks. The unusual lagoon depth of 59 fathoms back of the "sunken barrier" of eastern New Guinea, as above stated: the exceptional depth of 70 fathoms in the barrier-reef lagoon of Vanikoro in the Santa Cruz group; the depths of 60 or more fathoms on the bank that surrounds the Samoan island of Tutuila; the depth of 55 fathoms in the little Clipperton atoll, only two miles in diameter, in the eastern Pacific, of which further mention is made below; the depths of 60 and 70 fathoms on great Saya de Malha bank in the southern Indian ocean; the depths of 50, 60 and 70 fathoms or more on the unrimmed bank that surrounds the small island of Fauro in the the northwestern part of the Solomon group; the depths of 50 or 60 fathoms on the bank rimmed by a submerged reef along the northwestern side of Palawan, the long, southwesternmost member of the Philippine group; and the depths of 50 or 60 fathoms in the Macclesfield bank, a large "drowned atoll" of the China sea—all these appear to be additional cases of relatively active and recent subsidence. Hence if these exceptional lagoon and bank depths are, as the advocates of the Glacial-control theory would probably admit, determined by a fairly active subsidence of recent date which could not be altogether compensated by aggradation, a slower subsidence may be regarded as having been better compensated in lagoons of more ordinary depth. This is especially true in examples where a submergence of more than 50 fathoms is indicated by the forms of the partly submerged valleys, as in Tahiti, Borabora, and other members of the Society group; in Kandavu and other members of the Fiji group; in New Caledonia; and elsewhere.

In any case, the moderate and fairly accordant depths of reef-enclosed lagoons in regions of subsidence need not occasion surprise; for the very presence of reefs around the lagoons shows that whatever relative changes of level have taken place in ocean surface and reef foundations, the changes cannot have been faster than the slow rate of reef upgrowth; and if reefs have been able to maintain themselves at sea level by upgrowth during such changes of level, lagoon floors may have maintained by aggradation a moderate depth appropriate to their area during the same changes. This aspect of the problem need not be pursued further here.

Evidence of Tagula and Its Satellites against Abrasion.—However probable the assumption of low-level platforms of abrasion may be for islands near the margin of the coral seas where the Glacial cooling of the ocean waters may have inhibited coral growth, it is extremely improbable for Tagula, which lies not far from the equator in the western and therefore warmest part of the Pacific. The presence or absence of an abraded platform around Tagula cannot, however, be so well settled by a general estimate of such probabilities and improbabilities as by a search for the plunging spur-end cliffs that should be visible around the coasts of the main island and its satellites, if a wide platform had actually been cut across the area of the present lagoon when the ocean surface lay some 30 fathoms below its present level. The search should be made especially on those parts of the island coasts which lie nearest to the barrier reef; for there the spur ends of the mountainous islands must have been attacked and cut back at least a mile or two, while the 10- or 15-mile platform was in process of abrasion where the lagoon is broadest; and spur-end cliffs at the back of a one- or two-mile platform ought still to show their upper parts as "plunging cliffs," even after the ocean which cut them has risen 30 fathoms.

But an examination of the charts discovers no spur-end cliffs on Tagula or, with a few exceptions noted below, on any of the Calvados islands; and the absence of such cliffs, especially along the middle of the northern side of Tagula (Fig. 17) where the barrier reef is replaced by a half-mile fringing reef, militates strongly against the occurrence of an abraded rock platform beneath the great lagoon. It may be added that Rossel island also (Figs. 2, 18 and 19) gives even more emphatic testimony of the same kind; for there the barrier reef, which makes a seven-mile loop to the east and a 25-mile loop to the west, fringes the island on the northeast and on the south with deep water near by; and if a 15-mile platform were cut southwest of Tagula and west of Rossel, a platform of significant breadth should have been cut by the lowered Glacial ocean on these exposed parts of Rossel, and the cliffs at the back of such a platform should be high enough to be visible as plunging cliffs above the normal ocean level today; but no such cliffs are charted there. Thus the testimony of Tagula and Rossel against abrasion by the lowered Glacial ocean is similar to that given by many high, reef-encircled volcanic islands, as I have shown elsewhere.*

* The occasional occurrence of clift volcanic islands is pointed out in some of my earlier articles: Clift islands in the coral seas. Proc. Nat. Acad. Sci., II, 1916, 283-288. Les Falaises et les récifs coralliens de Tahiti. Ann. de Géogr., XXVII, 1918, 241–284. The coral reefs of Tutuila, Samoa. Science, LIII, 1921, 559–565.

Nearly all the islands of the Calvados chain repeat the same evidence. For example, the eastern end of Yeina, the easternmost member (Fig. 6), lies from a mile to less than half a mile from the barrier reef, outside of which a rapid descent is made to depths of over 100 fathoms; yet the chart gives no indication of shore cliffs; similarly, the northern side of Pana-tinani or Joannet island, the largest and next-to-easternmost member of the series (Figs. 12 and 13), is without cliffs, although it lies only three or four miles back of the barrier reef. If the northern compartment of the lagoon be underlaid by a platform 10 miles wide at its middle and the southern compartment be underlaid by a platform 20 miles wide, surely both Yeina and Pana-tinani should be well clift on their exposed northern sides; but they are without cliffs there.

The prevailing absence of plunging cliffs on the larger islands at least should not be ascribed to imperfect charting, for around the exposed northern side of Panniet (Fig. 3) cliffs are clearly represented. If similar cliffs were shown back of the fringing reefs of Tagula and Rossel, the case for abrasion during the lowered stand of the Glacial ocean would have support; in their absence it loses that support. Furthermore, the cliffs of Panniet plunge into deep water; soundings of from 100 to 230 fathoms are charted within 2000 feet of the shore, thus indicating a much steeper slope below sea level than that by which the visible island rises to its 700-foot summit 6000 feet inland. Hence, if the Panniet cliffs should be taken as the work of the lowered Glacial ocean, a strong Postglacial subsidence would have to be assumed in order to lower the cliff-base platform to its present considerable depth. That assumption is just as unfavorable to the Glacial-control theory as the denial of its abrasional process. Again along the northeastern coast of Misima, here reproduced in Figure 15, a cliff is well shown on the chart, and the legend is added: "Cliffs from 100 to 200 feet high;" thus indicating their exceptional nature; these cliffs may be the face of one of the elevated coral reefs mentioned by Maitland. If similar cliffs occurred on other islands they would presumably have been charted. As they are not charted, it may be believed that the islands are prevailingly not clift, and in the absence of cliffs, except for the few instances noted, it cannot be believed that Tagula and its satellites were without defense by living reefs while the ocean was lowered in the Glacial period.

Profiles of the Calvados and Other Islands.—As the foregoing descriptions of the shore features of the Calvados and other islands are based only on Admiralty Charts 2124 and 1477, it was felt desirable, although the charts bear internal indications of accuracy, that they should be supplemented by more direct evidence as to the presence or

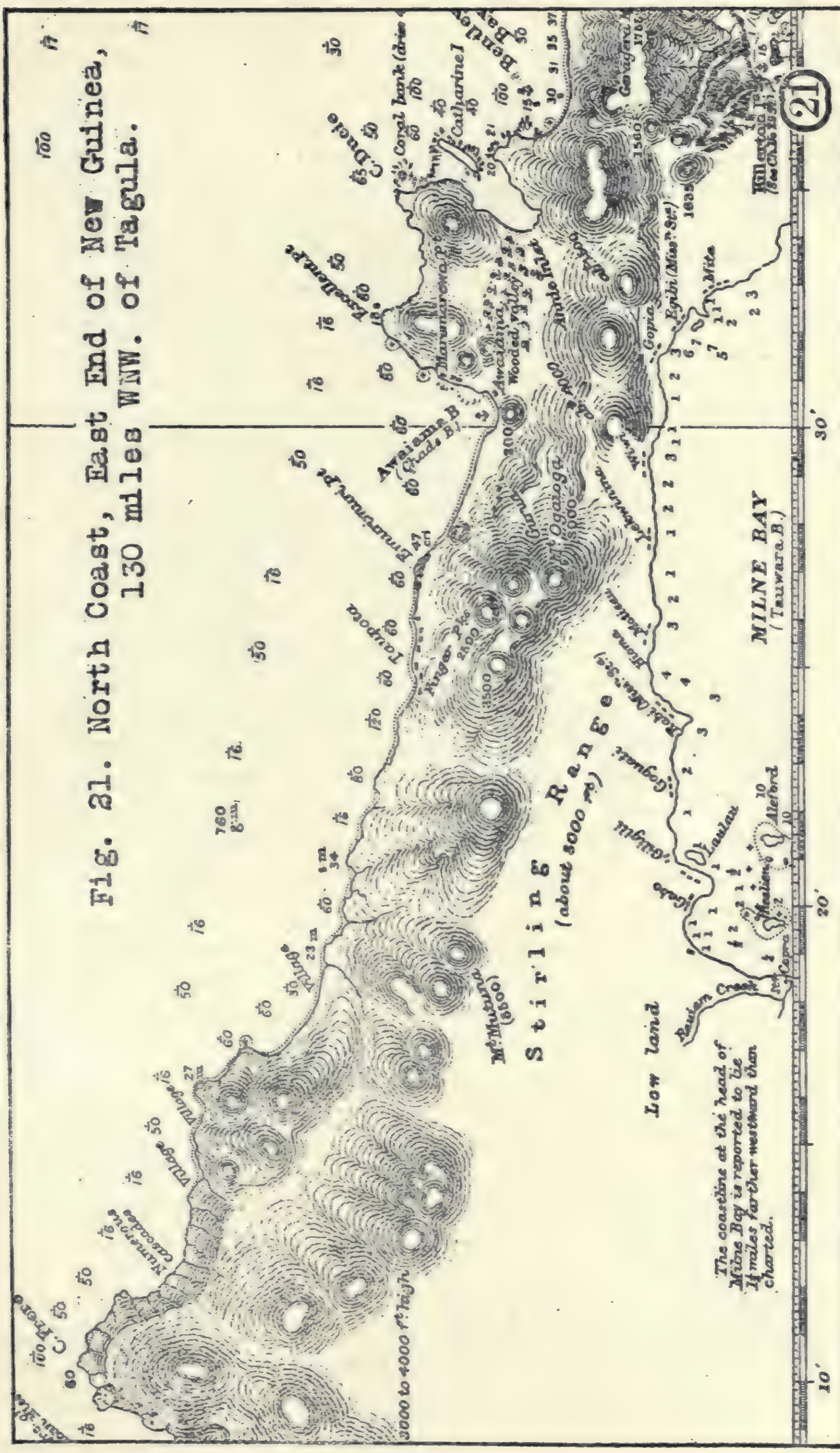

Fig. 21. North Coast, East End of New Guinea, 130 miles WNW. of Tagula.

absence of plunging cliffs. I therefore wrote to the office of the British Admiralty in London, asking whether it was possible to secure sketches of the islands from the officers who had made the surveys on which the charts are based; and in reply was given the address of Admiral Sir Mostyn Field, who while holding the rank of Lieutenant Commander in the Royal Navy was in charge of the surveying ship " Dart " when the survey of the Louisiade group was made in 1887-88, and who was kind enough to send me a number of leaves from his sketch book containing carefully drawn profiles of a large number of islands, as seen from stations on island summits in the Calvados chain. The positions of these stations are shown by small circles in Figure 1. They are situated on the islands of Gulewa (west), Maturina, Bobo-eina (this island is included in Figure 10), and Abaga-gaheia (east). The profiles, a number of which are here reproduced in Figure 23, leave no doubt whatever that, with the few exceptions to be noted, the islands of the Calvados chain and nearly all of the outpost islands are not clift, and thus make it altogether unreasonable to assume that the present lagoon is underlaid by a platform of abrasion. Had such a platform been cut by the ocean waves, there is no ground for imagining that wave work should continue 10 or 20 miles and then stop just short of cliffing the islands of the Calvados chain, to say nothing of the outposts. Thus an essential postulate of the Glacial-control theory and an essential process that follows from it—the inhibition of reef growth during Glacial epochs, and the abrasion of platforms at a standard depth by the lowered Glacial ocean—cannot apply to the Tagula reef-system. However that great barrier reef was formed, its broad lagoon floor must be explained without the aid of a smoothly abraded underlying platform.

This conclusion agrees with the results gained from the study of several Fiji islands, which, although bordered by fringing reefs along certain stretches of their shore line, have no plunging cliffs back of such reefs: witness especially the southwestern side of Viti Levu, the northeastern point (Cape Undu) and part of the southern side of Vanua Levu, and the southeastern side of Ngau. The same conclusion is further confirmed by the absence of plunging cliffs on the seaward side of a number of sub-mountainous islands that rise from the lagoon of the Great Barrier reef of Australia, although small cliffs have been cut upon them at present sea level by the lagoon waves.

Exceptional Steep-Margined Islands.—The exceptional steep-margined islands are ten in number, all of small size. They have irregular crests and are steep only near the shore. Eight of them lie just east of the middle of the Calvados chain, as shown in Profile 1-2 of

Fig. 22. N. Coast, New Guinea, 315 miles NW of Tagula.

(22)

Figure 23. Two of these, Mabneian and Panangaribu, are steep on the north; the northern reef is seven or eight miles distant. The five others of the eight, Einamu (not shown in the profiles), Panantanian (continued from Profile 1 into Profile 2), Pana Kuba, Pana-numara, and Leiga (not to be confused with an outpost of the same name in the northern part of Figure 11) are steep on the south; the southern barrier is distant about 15 miles. Gigela is a somewhat larger island not shown on the profiles here reproduced; its spurs are a little steeper than most of the others near their ends, but not so precipitous as those just named. The outlines of two islands, Bobo-eina and Bagaman, do not agree in Profiles 3 and 4; Profile 3, drawn from the nearer of two observing stations, shows the islands with sloping spurs; Profile 4, drawn on a somewhat larger scale from a more distant observing station, shows them with steep spur ends. As the nearer profile is probably the more trustworthy these two islands are not included among the clift islands.

The other two of the 10 steep-margined islands are outposts in the barrier southwest of the west end of the Calvados chain; they are Panasia or Real and Pana-vara-vara or Rugged islands; both are shown with cliffs in Profiles 5 and 6. Fortunately these are among the few islands the composition of which is reported by Maitland; they are colored on his map as consisting of "uplifted coral limestones." The first is exceptional in being represented as clift on the chart (Fig. 9); it is two miles long and 530 feet high and is described by Maitland as looking like a "raised atoll;" the other is one-half mile long and 345 feet high. The profiles of these two outposts in Admiral Field's sketches are similar to those of the other steep-margined islands above named, and dissimilar from the great majority of islands in the group, which have sloping spurs; and Panasia, like Pana-vara-vara, has a curved crest, not at all like the level crest of a raised atoll, such as Maré or Lifu in the Loyalty group north of New Caledonia. Hence, I am inclined to regard both these outposts not as atolls but as islands of some non-limestone composition, with raised barrier or fringing reefs, more or less eroded, around their flanks. In this respect they are therefore representative of what all the other Calvados islands are supposed to be, insofar as they partook of the uplift that is believed to have elevated the northwestern part of the Tagula barrier. But while most of the uplifted islands have lost their fringing-reef benches by erosion, these two outpost islands like the eight other steep-margined islands seem to have preserved enough of their uplifted reefs to give them the appearance of being clift. It would surely be most arbitrary to accept the steep slopes of those ten exceptional islands as clift by wave action during the abrasion of a low-level platform across the area of

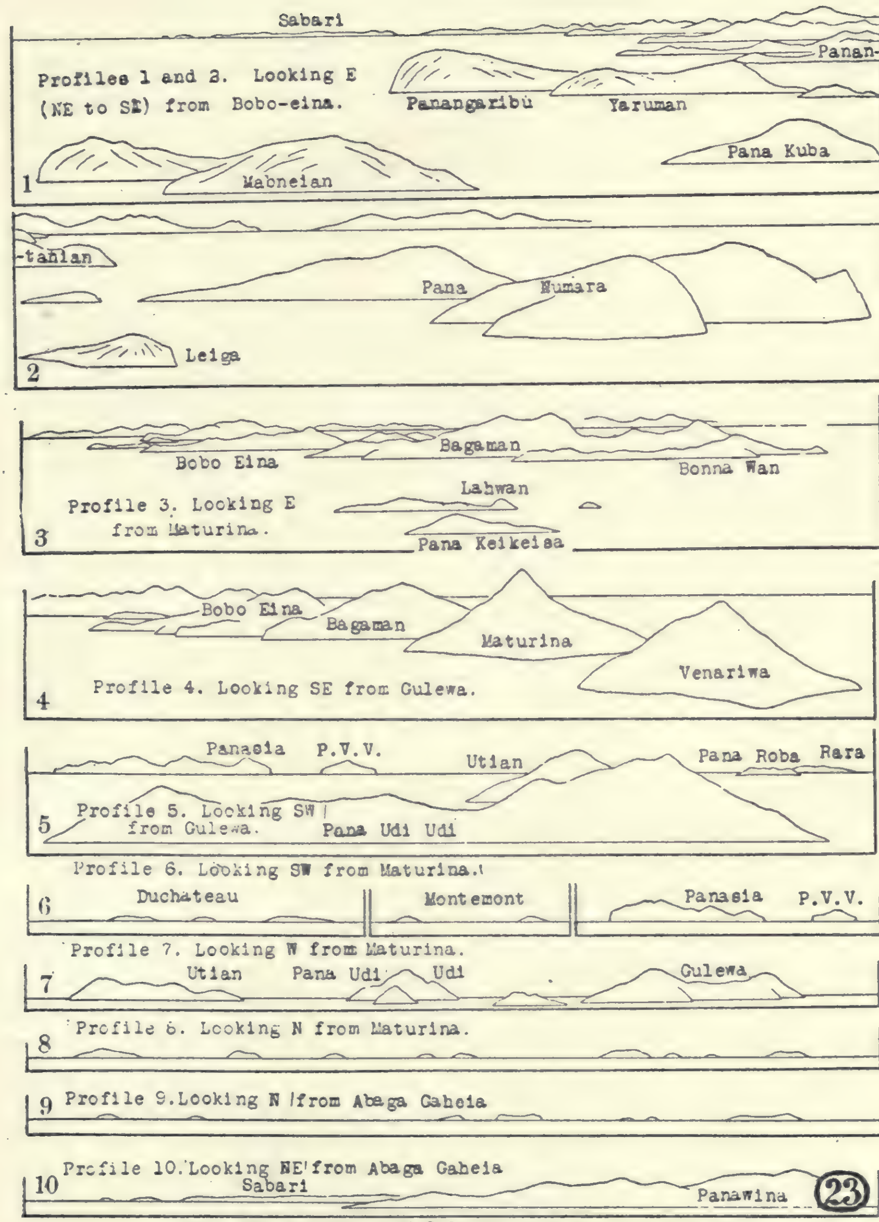

Fig. 23. Profiles of Calvados and Outpost Islands.

the present Tagula lagoon, for the great majority of the islands, some of which are in much more exposed positions than the six first named of the steep-margined islands, nevertheless testify against abrasion. Thus several examples of islands with gradually sloping spurs in the east-central part of the Calvados chain are shown in the neighborhood of the exceptional steep-margined islands in Profiles 1 and 2; others in the western part of the chain are shown in Profiles 5 and 7. The occurrence of steep-margined and gently sloping islands together in the Calvados chain favors the special explanation for the steep-margined islands given above.

Evidence of Outpost Islets against Abrasion.—The unique outpost islets of the Tagula barrier reef give even stronger evidence against abrasion than that offered by the majority of the inner islands. Had the outpost islets originally been small and unprotected by living corals during the lowered stand of the ocean in the Glacial epochs, they should, especially if they are composed of reef limestones, have been completely cut away by wave attack if it continued long enough for the abrasion of the 15-mile platform which, according to the Glacial-control theory, should underlie the broad southern compartment of the Tagula lagoon. Had the outposts been originally of larger size than now—and they must have been larger than now when the ocean was lowered—they should today present well-developed plunging cliffs on their exposed sides; but except in the cases of the two limestone islands above specified and a small outpost in Profile 9, no such cliffs are shown on the outposts on chart or profiles. Moreover, while the northern outposts exist in their present number, and still more while they existed in greater number and in greater size during the lowered stand of the Glacial ocean, it would seem impossible for the waves of the lowered ocean to abrade the ten-mile platform in the area of the northern lagoon compartment behind the outposts. The testimony of the outposts is therefore strongly against abrasion as postulated in the Glacial-control theory. It should be noted, however, that as far as the profiles of these small islets are concerned, they were all drawn from the summits of larger islands in the lagoon. Hence their exterior slope is not seen. But if effective abrasion had taken place, the ends of the outposts in the line of the barrier reef should have been clift about as strongly as their outer sides; and the profiles show the ends to be sloping, with one exception in Profile 9. Many of the profiles are small; but if so small an islet as Pana-vara-vara is drawn carefully enough to show its cliffs, the prevailing absence of cliffs in the other profiles may be taken to prove absence of cliffs on the islets themselves.

Beginning in the southwestern part of the barrier-reef circuit, the three Duchateau islets, charted in Figure 7, are shown in Profile 6 along with the two Montemont islets which are charted in Figure 8, a little farther west. After passing around the southwestern curve of the barrier, the limestone-rimmed islets, Panasia and Pana-vara-vara, already mentioned, are encountered; they are charted in Figure 9 and drawn in Profiles 5 and 6, as already noted. Farther northeast are the little islets, Rara and Pana-roba, which, with Utian, are charted in Figure 9, and drawn in Profile 5. Utian is particularly significant because it is said by Maitland to consist of volcanic rocks and because of its embayed outline on the ocean side. Between it and Gulewa lies Pana-udi-udi, of unknown composition; this island is seen end-on in the distance in Profile 7, and in a nearer side view in Profile 5. The contrast between the sloping profiles of Utian, Pana-udi-udi, Gulewa, Pana-roba and Rara and the clift sides of Panasia and Pana-vara-vara is significant. The little outposts in the northern loops of the barrier reef, several of which are charted in Figures 10, 11 and 12, appear, with one exception, to have gentle slopes; several of them are drawn in Profiles 8 and 9. Sabari, the longest outpost, is charted in Figure 12. No exterior profile of this island is available, but its northwestern end, which ought to be clift if the lagoon floor is underlaid by an abraded platform, has a gentle slope, shown in Profiles 1 and 10; and two minute outposts near by are in line with it to the northwest. The Calvados island, Hemenahei, which lies a short distance south of Sabari, is not charted as having cliffs in Figure 12.

In view of these well certified facts of form, it seems out of the question to believe that the northern compartment of the Tagula lagoon is underlaid by an abraded platform; and if it is not, there is no sufficient reason for thinking that the southern compartment is so underlaid. This conclusion is confirmed by the non-clift margins of the slender Renard islands (Fig. 16), about 10 miles north of the Tagula barrier. They are composed of uplifted reef limestones, as above noted, and are surrounded by a fringing reef with deep water near by; they surely ought to have been clift by the lowered ocean of the Glacial period if it abraded extensive platforms elsewhere, and if reef-building corals were so weakened as not to be able to withstand the waves. But the chart of these islands shows no signs of cliffs around them.

It is true that special conditions may be imagined under which platforms may have been abraded, even if the outpost islands now rise in the enclosing barrier reef; but the conditions are so exceptional that they are unacceptable. For example, the outpost islets might be imagined to be young volcanic islands, built up after a platform had been abraded and after the reef had grown up from it; but this demands

that a considerable number of volcanic vents should conspire to arrange themselves in highly specialized positions along the platform margin. Moreover, Utian, although certified to consist of volcanic rocks, has an embayed outline strongly suggestive of elaborate dissection since its eruption; it must be much older than the reef. Again, the long and narrow Sabari outpost is, in view of its form, much more probably a remnant of an uplifted and eroded reef than a volcanic island. Finally, two outposts, Panasia and Pana-vara-vara are certified to consist at least in part of limestone; their presence indicates an uplift in this district of 100 feet or more; yet the lagoon thereabouts is of ordinary depth. Hence their uplift must have taken place before the present lagoon floor was formed. As pre-existent islands they ought, according to the Glacial-control theory, to have been largely cut away, yet each of them now possesses a slender point directed seaward. They must therefore have been as well protected by living reefs while the ocean was lowered as they are today. Thus we are again compelled to reject an important postulate and an essential process of the Glacial-control theory, as far as Tagula is concerned. However, it should be remembered that that theory may apply to islands near the margin of the coral seas, even if it does not apply to Tagula and to many other islands over the greater area of the coral seas.

Clift Volcanic Islands Elsewhere.—In order to emphasize the contrast of the gently sloping islands of the Tagula region with the precipitous cliffs of unquestionably abraded volcanic islands, a view of Lord Howe island, received through the kind attention of Mr. E. C. Andrews, Department of Mines, Sydney, Australia, is here introduced in Figure 24. This island is a small volcanic residual which rises from a submarine bank measuring 8 by 12 miles across and from 20 to 40 fathoms deep, between New Zealand and Australia, at the margin of the present coral seas. According to the best interpretation that I can make, the bank consists of a barrier reef and its lagoon floor, which were formed in Preglacial and Interglacial times around a volcanic island, but which were truncated in the Glacial epochs when the reef-building corals were killed and the lowered ocean attacked the central island. In other words, this island and bank, like a few others in similar marginal position with respect to the coral seas, actually represent —but with two significant exceptions—the processes which, under the Glacial-control theory, are supposed to have been operative over nearly the entire extent of the coral seas. The two exceptions are that the reef foundation has probably subsided during the formation of the barrier reef; and that no reef has here grown up from the abraded platform in the present Postglacial epoch, presumably because the tempera-


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tures prevailing in this epoch are somewhat lower than those that prevailed in earlier non-Glacial epochs, especially in the last Interglacial epoch. The imposing cliffs of Lord Howe island, 600 or 800 feet in height, are therefore to be ascribed to precisely such abrasion as is assumed, under the Glacial-control theory, to have been widely operative in the coral seas; but the wide operation of this process seems inadmissible because the great majority of high islands within the barrier reefs of the coral seas are not clift. This aspect of the coral-reef problem will be dealt with in a special article on the "Marginal belts of the coral seas," to be presented to the Geological Society of America for publication in its Bulletin.

Bearing of the Tagula Lagoon on Other Lagoons.—The theory that barrier-reef and atoll lagoons are underlaid by nearly level platforms abraded around stationary islands is not based on any direct observation of the inferred platforms, for they are, of course, inaccessible in the case of sea-level reefs, and no such platforms have been discovered in the case of elevated reefs. Indeed, both the existence of abraded platforms and the still-stand of the islands around which the platforms were abraded are suppositions which appear to have been introduced into the Glacial-control scheme for theoretical reasons: First, because it was believed that the smoothness of lagoon floors is greater than could have been produced by the accumulation of sediments on uneven foundations, now subsided to a considerable depth; and second, because it was believed that the depths of lagoon floors are more nearly alike than they could be if they had been built up on subsiding foundations.

As to the second of these suppositions, it has been pointed out on an earlier page that the actual depths of many reef-enclosed lagoons vary from 10 fathoms or less to 80 fathoms or more; hence, in so far as the smaller lagoons have smooth floors, their smoothness must be due to smooth aggradation whether their rock foundation is an abraded platform at a standard moderate depth, or an uneven mountain mass at a greater depth. And it has already been noted that, by whatever theory coral reefs are explained, small reef-encircled lagoons should be as a rule shallower than large ones, for such variation of depth is a natural consequence of the fact that the waste inwashed from each linear foot of reef front will have a smaller interior area to aggrade in a small lagoon than in a large one. It is in accordance with this rule that the little reef loops in the northwestern arc of the Tagula barrier are much shallower than the two large compartments of the main lagoon; but this has no direct bearing on the theory that the reef and

the lagoon are underlaid by a flat platform cut on a still-standing foundation.

On the other hand, as to the two above-named suppositions, it appears from the facts and inferences already presented concerning the non-clift spur ends of Tagula and its satellites, and more particularly from the facts and inferences concerning the outpost islets of the Tagula barrier, that the northern compartment of this great lagoon cannot be underlaid by a platform abraded on a stationary foundation; for there is good evidence in support of the double conclusion that abrasion has not taken place and that the island has not stood still. Hence we are constrained to believe that this remarkably smooth lagoon floor has in all probability been built up by slow and long-continued aggradation during the similarly slow and equally long-continued subsidence of the uneven foundation on which the enclosing reef has its deeply submerged base, although the possibility of interruption in the regular continuation of these processes by reason of a temporary uplift of sub-recent date has been pointed out.

The presence of a smoothly abraded platform is therefore not essential to the production of this smoothly aggraded lagoon floor; and if such a platform is not essential in the northern compartment of the Tagula lagoon, which measures about 25 by 10 miles, it cannot be essential in the larger southern compartment either, or in any other lagoon in the whole breadth of the Pacific, even though the reefs which enclose such lagoons do not contain outpost islands to serve as local witnesses against the possibility of platform abrasion. But this is not all.

Both compartments of the Tagula lagoon are of normal depth, or of slightly less than normal depth, in their broader parts for lagoons of their large size; the less depths in their narrower parts, as in Figures 6, 12 and 13, and in the smaller lagoons not far away, as well as in the small lagoons of the Tagula reef loops, are also normal for lagoons of smaller size. All these normal depths occur in spite of the abundant evidence against the stability of Tagula and in favor of its long-continued subsidence of great amount, and in spite of the further evidence for the instability of the Louisiade region as a whole given by the elevated reefs of Misima and by the provisionally adopted explanation of the Tagula outposts by elevation, erosion and subsidence. Hence it is no more necessary to assume that Tagula has long been stable in order to account for the normal depth of its great lagoon than to assume that a platform has been abraded around it in order to account for the smoothness of the lagoon floor. Slow aggradation by evenly distributed sediments during the slow subsidence of an uneven foundation, possibly aided by erosion during emergence, as noted above,

should therefore be regarded as sufficient to develop the Tagula lagoon floor at an ordinary depth as well as to give it a smooth surface. If this be true for the Tagula lagoon which is situated in a region of unquestioned crustal disturbance, it may be equally true for reef-enclosed lagoons in other parts of the Pacific where crustal conditions are not so well known.

In view of the facts and inferences thus summarized, as well as in view of similar summaries of evidence previously published, the presence of smooth lagoon floors at ordinary depths appropriate to their size can not be accepted as sufficient proof of the long-continued stability of coral-reef foundations in the open Pacific, or for their abrasion to a smooth platform at a standard depth by the waves of the lowered Glacial ocean while the reef-building organisms were weakened or killed by the chilled ocean waters. And as the stability of reef foundations and their abrasion to platforms of standard depth both appear to have been assumed in the Glacial-control theory, largely because these assumptions were thought to be necessary in explaining the smoothness and the roughly accordant depths of many lagoon floors,—among which, however, the Tagula lagoon was not included—both assumptions may now be regarded as not generally necessary, although one or both of them may of course still be accepted as far as need be wherever demanded by direct evidence. Such evidence is, in my belief, afforded by certain islands near the margin of the coral seas, as will be shown in the later article already referred to.

Outpost Islets Elsewhere.—High islands of various dimensions rising from the lagoons of barrier reefs are common enough; but small and high islets rising from the reefs themselves—that is, outpost islets in the sense of that term as here used—are of rare occurrence. One of the best examples is furnished by the islets on the submerged reef that loops some six miles westward from the island of Rotuma, north of Fiji. Three outpost islets here rise to heights of 190, 860, and 1920 feet, and all appear to be volcanic, as far as they are described.[8] The highest and largest is clift on its exposed northwestern side, but the main island is not clift on its southeastern or windward side, where it is bordered only by a very narrow fringing reef. The relations of main island, outposts, and reefs here need further study. The Fiji archipelago offers only one well-marked example of an outpost islet in the atoll of Ngele Levu, the northeasternmost member of the group.

[8] J. S. Gardiner. The Geology of Rotuma, Quart. Jour. Geol. Soc., LIV, 1898, 1–11. The Coral reefs of Funafuti, Rotuma and Fiji . . . Proc. Camb. Phil. Soc., IX, 1898, 417–503.

According to Agassiz,[9] this atoll is of pear-shaped outline, measuring 14 by 7 miles, with a lagoon 10 or 15 fathoms in depth; three islets of coralliferous limestone rise from the eastern or windward arc of the reef to heights of about 60, 40 and 30 feet. It is difficult to believe that these outpost islets could have survived if the lagoon be underlaid by an abraded platform. A less marked example is afforded by the smaller reef of Wailangilala, 40 miles farther south. It is about three miles in diameter and its lagoon has depths of 22 and 23 fathoms; an islet on the eastern side of this reef has a height of 15 feet, hardly sufficient to warrant its being called an outpost; the lighthouse upon it is familiar to travelers between Fiji and Hawaii. According to Agassiz, under whose direction a boring was made here to a depth of 85 feet, the islet is not a part of the present reef, but "the fragment of an ancient island of larger size, which once covered the whole area of the lagoon;" but, if so, its survival on the windward side while a sub-lagoon platform was abraded seems impossible. Hence in both these cases, as at Tagula, abrasion by the lowered ocean must have been prevented by the presence of living corals. If these limestone outpost islets were thus protected from abrasion, all other islands in Fiji must have been similarly protected.

Cosmoledo reef, between the northern end of Madagascar and Africa, measures 9 by 6 miles, with a reef flat from one to one and a half miles wide; the enclosed lagoon is only 3 or 4 fathoms deep. Several islets with heights up to 50 feet arise from the reef flat. Not far away Aldabra island is a raised atoll so little dissected as to preserve an almost continuous rim; it measures 17 by 5 to 7 miles, with a height of 20 feet; the enclosed lagoon is either dry or very shallow. The islets on the Cosmoledo reef are therefore probably remnants of an emerged reef of earlier origin.

A typical example of a little outpost islet—a mere "rock"—is offered by the lonesome Clipperton atoll in the eastern Pacific (Lat. 10° N., Long. 109° 30′ W.), which is represented in an Admiralty chart as two miles in diameter, with a lagoon in which 65 soundings include seven with the unusual depths of 40, 48, 52, 45, 42, 40, and 55 fathoms. The small volcanic rock, 500 feet across and 62 feet high, rises from the southeastern arc of the reef, and is regarded by Wharton as a remnant which has resisted wave attack.[10] And so it may be, as it stands in a relatively cool part of the Pacific, where coral growth may have been inhibited during the Glacial period. But it may also

[9] A. Agassiz. The Fiji islands and coral reefs. Bull. Mus. Comp. Zool., XXXIII, 1899, 1–167; see p. 43–47.

[10] W. L. J. Wharton. Note on Clipperton atoll (Northern Pacific). Quart. Journ. Geol. Soc., LIV, 1898, 228, 229.

be the summit of an unsymmetrical volcanic peak, owing its present eccentric position as well as its small altitude to subsidence, as is further explained below. In any case its lagoon is so deep that a sublagoon platform cannot have been abraded by the lowered glacial ocean, unless subsidence has taken place since.

Aitutaki, a small volcanic island and reef in the Cook group, may be here mentioned not so much because this island, like Panniet, occupies the northern corner of the triangular reef which measures about six miles on a side, but because of Agassiz' description of it. He states that "volcanic outliers crop out at many points on the barrier reef," as if they were outpost islets, and regards the island as "an excellent example of a volcanic rock flat upon which corals are growing."[11] If the lagoon, which is only four fathoms deep, be truly underlaid by such a rock flat, the flat cannot have been produced by abrasion if the rocks seen "at many points" in the reef are properly described as volcanic outcrops; while they survive, the space within them could not have been attacked by the waves; but further observation of this example is desirable.

Another Lesson from the Tagula Outpost Islets.—It may be conceived that coral reefs grow up vertically from their foundations, so as to maintain the outline and the perimeter of their lagoon unchanged; or that they grow upward and outward, so as to increase the perimeter of their lagoon; or upward and inward, so as to decrease it. This aspect of the coral-reef problem has been discussed in one of my earlier papers,[12] with the conclusion that outward upgrowth is possible around very slowly subsiding foundations, especially if the adjoining ocean be of moderate depth; but that inward upgrowth must take place from foundations that subside more rapidly, especially in a deep ocean. Several of the Tagula outposts, which are believed as already explained to represent the diminished summits of small residual islets composed of elevated reef limestone, favor the latter conclusion for the following reasons: Most of these outposts stand in excentric positions with respect to their reef loops, and in a good number of cases they are so far excentric that they rise from the reefs themselves instead of from the little lagoons that the reefs enclose. Thus they are outpost or excentric islets in a double sense; they not only rise in the general course of the great barrier reef outside of the Tagula lagoon, but many of them rise from the reefs of the small loops which make up the north-

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[11] A. Agassiz. The coral reefs of the tropical Pacific. Mem. Mus. Comp. Zool., XXVIII, 1903; see p. 170.

[12] Extinguished and resurgent coral reefs. Proc. Nat. Acad. Sci., II, 1916, 466-471.

western arc of the great barrier. The outpost summits could not be contained in the reefs if the reefs had been formed by outward upgrowth from a lower and therefore larger contour line on the submarine slope of the outpost islet. Even after vertical upgrowth a reef could not include an islet summit unless it had an overhanging face on one side, and that is altogether improbable. Nor should an excentric position of an outpost result if its submarine slopes had the form of a symmetrical cone, from which a reef loop was formed by inward upgrowth.

But if an original outpost islet had an unsymmetrical form and an excentric summit, with a much steeper slope on one side than on the other, then a part of a reef formed by inward upgrowth might cling to the steeper slope and eventually include the excentric summit, while the rest of the reef formed by inward upgrowth from the gentler slope would enclose a diminishing lagoon. Hence at least some of the reefs in the loops of the northwestern arc of the Tagula barrier have probably been formed by inward upgrowth. The same is probably true of the wide fringing reef around the Renard islands (Fig. 16), where some minute islets rise from the outer margin of the reef; and also of the barrier reefs which become fringes on the northern side of Tagula itself (Figs. 6 and 17), and on the northeastern and southern sides of Rossel (Figs. 2, 18 and 19). Similarly the excentric position of the outpost rock in Clipperton atoll, above mentioned as standing alone in the eastern Pacific, is like that of the Tagula outposts well explained by the inward upgrowth of its reef from the submarine slopes of an unsymmetrical island, now mostly submerged.

Tagula Supports Darwin's Theory of Coral Reefs.—It appears from the foregoing account that Tagula with its satellites and outposts gives much better support to Darwin's theory of coral reefs than to the Glacial-control theory. Unlike the scattered volcanic islands of the central Pacific, which have each been formed separately and independently of one another, the various islands of the Louisiade group are not of separate origin, but are related parts of a long mountain system; and as such the evidence that they furnish of crustal deformation, advanced erosion, and strong regional subsidence seems well established. On the other hand, as they give no evidence of having been significantly modified by abrasion, it appears reasonable to suppose that they have been continuously encircled by defending coral reefs during their subsidence. Hence the Tagula barrier reef is best explained by long lasting upgrowth, and the lagoon floor by long lasting aggradation, modified by recent uplift, erosion and subsidence, as above proposed; both the reef and the lagoon deposits being presumably based on the uneven

surface of the subsided mountain range. The subsidence of the region may well have been intermittent, and the ocean surface may very presumably have suffered Glacial changes of level during the later phases of the subsidence; but the reefs around Tagula, as well as around Rossel and Deboyne, give no visible indication of having suffered abrasion during a time of inhibited coral growth at any stage in their long existence.

It must be inferred, however, that in the southeastern arc of the Tagula barrier, where no recent uplift is indicated, reef upgrowth may have been temporarily interrupted if the lowering of the ocean surface in the Glacial epochs took place at a faster rate than the subsidence of that part of the reef foundation at those times, thus leaving the crown of the reef emerged. It must also be inferred that if emergence of the reef were thus caused, the reef-building organisms would have transferred their belt of growth from the outer side of the reef crown to zones farther and farther down the exterior slope of the reef. This seems reasonable, because during the lowering of the ocean surface, the waves would have progressively removed the loose fragmental and detrital material that normally accumulates on the reef slope below depths of 15 or 20 fathoms, and would have thus prepared a firm surface for the reef-building organisms to grow upon.

Similarly, it must be inferred that at each Interglacial epoch of rising ocean level, the reef-building organisms must have shifted their belt of growth upwards toward the former reef crown, and that as they ascended the slope they must have repaired the erosional damage suffered by the reef during its emergence; and that during each slow rise of the ocean surface, detrital material would accumulate on the exterior slope of the reef at depths below 15 or 20 fathoms, where corals had been growing while the ocean was lowered, and would thus tend to reconstitute the characteristic declivity by which most reefs descend into the deep sea; namely a declivity having a fairly strong slope to the moderate depth of about 40 fathoms where wave action is ineffective, followed by a steeper pitch to greater depths. Yet, probable as these changes of ocean level are, and reasonable as the inferences concerning the accompanying changes in organic conditions seem to be, no direct indication of their occurrence has yet been found. It is as if a moderate and recent subsidence of the region had lowered all records of the Glacial period to depths where they cannot be detected. In any case these records appear to have been subordinate to those consequent upon long-continued and great crustal subsidence.

The argument by which the above conclusion in favor of Darwin's theory has been reached is by no means infallible; it needs confirmation by a critical observation of Tagula, its satellites and outposts;

but in the meantime its validity seems to me highly probable. Let it be understood, however, that Darwin's theory does not postulate that all subsiding islands have subsided at a uniformly slow rate, so as always to permit the upgrowth of coral reefs from them; still less that all islands have subsided. The original theory postulates only that, where barrier reefs and atolls exist, the subsidence of their foundations has not been so fast that it could not be compensated by reef upgrowth and to a less degree by lagoon aggradation. The theory should be amended today so as to postulate that, where barrier reefs and atolls exist, the subsidence of their foundation together with any rise of ocean level that has taken place during the subsidence, has not caused a submergence so rapid that it could not be compensated by growth of the reef and the aggradation of the lagoons; but as far as Tagula is concerned, changes of ocean level do not seem to have caused any great modification in the form of the reef system from that which it would have if subsidence had taken place in an ocean of unchanging level.

On the other hand, the present barrier reefs of the Louisiade group should not be regarded as uninterrupted upgrowths from the original shore line of a continuous New Guinea-Louisiade mountain range before subsidence of the region began; for in that case the reefs should be as continuous now as the shore line was then, instead of now being resolved into separate barriers around the separate islands. When subsidence began, an initial reef presumably grew up from the original shore line, first as a continuous fringe, except for breaks near stream mouths; then as an equally continuous barrier, except for interruptions at passes. But in time the first generated reef was probably drowned by an unusually strong subsidence, and thereupon fringing reefs of a second generation, of less total perimeter than before, would, according to a special condition of Darwin's theory quoted below, be established around the new shore line. Such an extinction of barrier reefs, followed by a new generation of fringing reefs at a higher level, may have taken place several times, especially in the eastern part of the mountain system, where subsidence appears to have been greater than in the western part; and after each time of such reef extinction, the perimeter of the new reefs and the area included within them must have been smaller than before. Moreover, when subsidence submerged some of the passes in the mountain crest, the continuous shore line of the original mountain system must have been converted into several separate or independent shore lines around the separated culminating parts of the system between the submerged passes; and each such part would thereupon become an island. Any later subsidences that were strong enough to drown the reefs would result in the still further separation of the independent islands and reefs. The present arrangement of

well-separated barrier reefs around the farther separated islands of the Louisiade group has probably resulted from some such sequence of changes.

CONFIRMATION BY POCKLINGTON REEF.—Fortunately, the sequence of changes thus sketched is not left altogether to the imagination. The Louisiade region itself affords fairly direct evidence of precisely such a change as has been supposed; that is, of so rapid a subsidence in its eastern part that reef upgrowth could not keep pace with it. It has already been stated that all the larger islands are composed of steeply inclined and greatly eroded schists and slates, and that rocks of a similar character occur in the mountains along the northern coast of eastern New Guinea. In view of these facts it is generally believed by all writers on the subject that the mountain system to which the Louisiade islands as well as the New Guinea ranges genetically belong originally extended to the east of Rossel, the farthest island now visible. This belief is sufficiently grounded in the fact that the rock structures of Rossel appear to be about as massive and as much disturbed and as deeply eroded as those of the islands farther west. Hence the mountain system must have been originally prolonged beyond the outermost island; just as the deformation by which the ancient mountain ranges of Brittany or of southern Ireland were produced and the subaerial erosion by which they were shaped must have originally extended into the Atlantic area much farther westward than the now visible peninsular ends of the ranges. It is therefore reasonable to conclude that the New Guinea mountain system as a whole once extended scores or hundreds of miles farther eastward than Rossel; that its western part, although having had ups and downs in its history, today forms a continuous mountain range in eastern New Guinea, because subsidence has not been dominant there; that an intermediate discontinuous part characterized by strong subsidence is now seen in the Louisiade archipelago, where, with the exception of Misima, the mountain range was, during the later stages of subsidence at least, depressed so slowly that compensating reef growth was possible; but that the easternmost part, now completely submerged, was during the later stages of subsidence, if not earlier, depressed either so greatly that it is now surmounted only by atolls, or so rapidly that no reefs could grow up to sea level from it. It is therefore especially interesting to learn that an atoll, Pocklington reef, 18 miles long and three wide, lies 100 miles eastward from Rossel. According to the British Admiralty Sailing Directions for the Pacific, Volume 1, the wreck of a large iron ship lay on the south side of the atoll in 1880. Soundings in this completely submerged part of the mountain system would be of special interest in connection with the

coral-reef problem. It is evident that submerged reefs as well as submerged mountain-top islands may here await discovery.

The Peculiar Case of Misima.—It should not be forgotten in this connection that, as already intimated, Misima (Fig. 4) affords evidence in its unconformable reef terraces of having subsided at times too rapidly for compensation by reef upgrowth, and thus gives good warrant for accepting not only the occasional rapid subsidence of Tagula and its neighbors as noted above, but also the rapid and greater subsidence and complete disappearance of the lost easternmost part of the New Guinea mountain chain, as just described. The unconformable reefs, high on the slopes of the mountains in eastern New Guinea teach the same lesson; and all these examples serve to correct the misapprehension, sometimes encountered, that Darwin's theory of coral reefs postulated a subsidence of islands no faster than reef upgrowth. As a matter of fact his theory was based on no such limited postulate. He recognized clearly that subsidence might be either slow or rapid; that existing reefs appear to have grown up where the subsidence has been so slow as not to drown them, and that reefs would be drowned if subsidence took place rapidly. The now elevated reefs of Misima are particularly pertinent here, for in so far as they were formed during pauses in a rapid subsidence preceding the recent emergence of the island, they, as well as certain sea-level fringing reefs, exemplify a type of reef formation in association with rapid subsidence that was clearly recognized as a possibility by Darwin, although he found no examples to verify its actual occurrence, as may be now pointed out.

The general understanding of Darwin's theory associates most fringing reefs with stationary or rising coasts, and there are undoubtedly many fringing reefs on coasts of those kinds; but the original statement of the theory contains the following significant passage: "If during the prolonged subsidence of a shore, coral-reefs grew for the first time on it, or if an old barrier reef were destroyed and submerged, and new reefs became attached to the land, these would necessarily at first belong to the fringing class."[13] Many fringing reefs in the Philippine islands appear, as I have elsewhere pointed out,[14] to have been thus formed, for they rest unconformably on the strongly eroded rocks of well-embayed shore lines. Although Darwin did not perceive the bearing of embayed shore lines or of unconformable reef contacts, these examples very clearly illustrate his idea that fringing reefs must be the first to form on a rapidly submerged coast, which during earlier and slower subsidence had been fronted by a barrier reef.

[13] C. Darwin. The Structure and Distribution of coral reefs, 1842, 124.

[14] Fringing reefs of the Philippine islands, Proc. Nat. Acad. Sci. IV, 1918, 197–204.

In the case of Misima, even if all of its unconformable terracing reefs were formed during pauses in emergence, the highest reef must have been formed during the pause that separated a preceding rapid and great subsidence from a following intermittent upheaval; that is, it must have been formed under the conditions specified by Darwin in the above citation. As already noted, the embayed shore line of Misima (Fig. 14) shows that its recent emergence is not so great as its previous submergence. This peculiar island is therefore in a sense intermediate between Tagula, Rossel and Panniet, on the one hand, as these islands are believed to have suffered on the whole a long-continued subsidence usually at so slow a rate as to develop large barrier reefs around extensive lagoons; and on the other hand the imagined easternmost original members of the Louisiade group which are believed to have subsided so fast that they have completely disappeared, leaving only a single atoll as a monument of their former existence.

The embayed but almost reefless northern coast of eastern New Guinea, as illustrated in Figures 21 and 22, is an excellent illustration of Darwin's principle that on a subsided coast the new reefs should be at first attached to the land, and should therefore necessarily belong to the fringing class. Not only so; that coast must also be regarded as one which has subsided rapidly because it is not fronted by an offshore barrier reef, and furthermore as one that has subsided lately because its fringing reefs of a new generation, as they may be called, are still extremely narrow. By far the greatest part of the coast in Figure 21 has no chartable fringing reef. Moresby reports that for 25 miles west of East cape, the coast is " washed by a grand, clear, reefless sea; a ship might literally sail with her sides rubbing against the coral wall which binds the shore, and find good anchorage in any of the bays where a breach is seen."[15] Farther northwest fringes of a significant breadth are developed on some of the sloping headlands around the embayed shore line of Mt. Trafalgar (Fig. 22), but other headlands have no reefs. The latest change of level by which the present configuration of this coast has been determined cannot therefore have been alone the Postglacial rise of sea level; for in that case the reefs should surely have been well formed, and they might well have included off-shore barriers as well as on-shore fringes; the latest change must have been a relatively rapid and very recent subsidence of the coast itself.

To return to the case of Misima: The absence of cliffs around the greater part of that mountainous island is peculiar. If it had been stable and had been as free from protecting reefs during the Glacial

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[15] J. Moresby. Recent discoveries in the southeastern part of New Guinea. Proc. Roy. Geogr. Soc., XVIII, 1873, 22–31; see p. 28.

period as it is now, its entire coast should have been cut back, and should today be bordered by plunging cliffs. Its freedom from cliffs, except along the northeast side where the cliffs are probably those of an emerged reef, indicates that it cannot have been in its present unprotected condition during the last Glacial epoch; it must then have stood lower, so as to be protected by the now emerged reefs, or higher, so as to be protected by now submerged reefs. Conversely, the plunging cliffs on the northern, unprotected side of Panniet (Fig. 3) suggest that, if the cliffs are wave cut, the island must have sunk since they were cut, for they do not descend to a shallow platform. Close study of these islands should yield interesting results.

The Value of a Single Example.—The chief interest attaching to Tagula in connection with the coral-reef problem comes from the evidence that it gives to the effect that its great barrier reef and broad lagoon floor have been formed by upgrowth and aggradation during the slow and probably intermittent subsidence of an uneven foundation; that the oscillations of ocean level and changes of ocean temperature during the Glacial period have left no recognizable marks on the islands or in the reef system; and that the broad lagoon floor within the reef has been aggraded to a standard depth without the aid of the special conditions and processes that are invoked in the Glacial-control theory. If the Tagula reef and lagoon floor have been formed in this way, many other reefs and lagoon floors may have a similar origin. Thus Tagula may be regarded as an important witness in the coral reef problem: but it does not stand alone. The evidence offered in the present paper on Tagula and its reef merely repeats and extends the evidence presented in several earlier papers on various members of the Fiji group, Tahiti in the Society group, New Caledonia, and the Great Barrier Reef of northeastern Australia.[16] It may be added that in Foye's recent study of Fiji he also was "unable to discover in these islands any evidence of Pleistocene wave-cut platforms;" and he was led to conclude that "the detailed history of the islands of Fiji shows that they have not been stable during recent geological time, and an adaptation of

[16] Problems associated with the origin of coral reefs. Sci. Monthly, II, 1916, 313-333, 479–501, 537–572.

Les falaises et les récifs coralliens de Tahiti. Ann. de Géogr., XXVII, 1918, 241–284.

Subsidence of reef-encircled islands, Bull. Geol. Soc. Amer. XXIX, 1918, 489–574.

The Great Barrier reef of Australia. Amer. Journ. Sci., XLIV, 1917, 339-359.

Coral reefs and submarine banks. Journ. Geol., XXVI, 1918, 198–223, 289–309, 385–411.

The islands and coral reefs of Fiji. Geogr. Journ, LV, 1920, 34–45, 200–220, 377–388.

Darwin's theory may apply to many of these islands."[17] The small outpost islets of the Tagula reef are evidently of especial significance in the argument above presented, and should be closely examined as to structure and form by any observer who has the good fortune to visit this remarkable reef system.

If the solution of the coral-reef problem depended chiefly on a study of coral reefs themselves, the importance of the individual study of different reefs would not be very great, because after the several classes into which they fall are recognized, sea-level reefs do not teach much from a geological point of view, however interesting they are zoologically. It is for this reason that the examination of atolls, except by deep borings, has been unproductive, so far as the demonstration of their origin is concerned. All the facts that they offer are explained with about equal competence by various coral-reef theories, if the postulated conditions and processes of the theories are accepted. The real question at issue, however, is not whether the conditions and processes postulated in various theories are competent to produce coral reefs, but whether those postulated conditions and processes correctly represent the invisible past facts of geological history. This question cannot be answered by a study of the reefs alone; the answer is difficult enough to find when all accessible facts regarding reef-encircled islands and reef-fronted coasts are also taken into consideration. Moreover, the conditions and processes that have possibly been involved in the formation of coral reefs are so varied that nothing less than a detailed geological examination of the islands and coasts which they border will suffice to determine what conditions and processes have been actually involved in the production of any individual reef.

This is, of course, as true for the Glacial-control theory as for Darwin's theory of coral reefs. Each theory leads to the expectation that reef-encircled islands as well as the reefs that encircle them may have various forms; and in view of the evidence furnished by Tagula as to the possible formation of an extensive flat-floored lagoon at a normal depth on a subsiding foundation without the aid of abrasion, it becomes all the more necessary to review the testimony of other islands that reefs encircle, instead of basing conclusions largely upon the form and depth of the lagoon floors that the reefs enclose. The testimony of islands near the margin of the coral seas is, as has already been noted, particularly important in this connection; and those islands will be examined elsewhere. In the meantime, the evidence here presented from the marvellous barrier reef of Tagula is believed to be worthy of special consideration by students of coral-reef origins.

[17] W. G. Foye. Geological Observations in Fiji. Proc. Amer. Acad. Arts and Sci., LIV, 1918, 1–145; see page 95.

TITLES AND ABSTRACTS OF PAPERS

WASHINGTON, 1921

Ellen Churchill Semple.

Presidential Address:—The Influence of Geographic Conditions Upon Current Mediterranean Stock-Raising.

Oscar S. Adams (Introduced by William Bowie).

The Problem of Representing the Earth's Surface on a Map.

The fundamental difficulty that we encounter in our attempts to make a plane map of the earth's surface is due to the fact that the shape of the earth is approximately that of a sphere and that a spherical or ellipsoidal surface cannot be spread out into a plane without stretching, tearing, or folding. In the map we must therefore expect distortions of shape or size and in many maps both are present. We often deceive ourselves by expecting that any map whatever ought to show us any quality that we may desire to know. It is necessary to realize that a map is merely a means by which we strive to picture things that cannot be exactly pictured on a plane surface.

If the area represented is small, the distortions may be less than we could detect by any measurements, and hence such maps may be considered accurate in all respects. When the area becomes extensive, it is necessary to be careful not to accept appearance for truth. We should always consider what the map is intended to show before passing judgment regarding any particular feature of the region represented.

The possibility of representing extensive regions on a map was illustrated by a number of slides, these also illustrating the limitations that should be expected in various types of maps.

Oliver E. Baker.

Significant Changes in the Utilization of Agricultural Land as Shown by the 1920 Census.

The statistics now available from the 1920 census show significant changes in the utilization of land during the decade. There was an increase in farm land of 84 million acres in the western half of the country, where arid and semi-arid lands of the public domain were being occupied under the Enlarged and Stock Raising Homestead acts, and a decrease of five to seven million acres in the humid eastern half of the country. At the same time the crop land in the eastern states increased 34 million acres. Since the eastern half of the country contributes 90 per cent of our agricultural products, it is evident that the increased production during the decade was secured by more intensive

utilization of the existing farm land and not, as heretofore, mostly by expansion of the agricultural area.

We have reached the stage in our agricultural development when there is practically no more good or even fair land left unutilized for farming. Although our improved land amounts to only 27 per cent of the land area, the land which remains unimproved is, with few exceptions, too wet or dry, too steep or stony or infertile, for the profitable production of crops without amelioration. The population of the United States is rapidly increasing, and this increasing demand for foods and fibres cannot for long be supplied by increasing the intensity of cultivation. The diminishing returns per unit of labor applied will soon enforce recourse to the less available land. The amount of such land, which it is possible by various means of amelioration to bring into use for crops, is probably over 300 million acres. It includes about 75 million acres of drainable and probably 30 million acres of irrigable land, perhaps some 175 million acres of forest and cut-over lands not requiring drainage, but in many cases deficient in fertility, and a considerable area of stony or infertile pasture land in the East and potential dry-farming land in the West.

Whether this nation will embark upon a vast enterprise of land reclamation, or whether it will depend on other countries, particularly the tropics, to meet the demands of an increasing population, for agricultural products, will soon become a pressing national problem. If, after mature consideration, it appears advisable to embark upon a policy of protection of agricultural industries, it is important that the expansion of the agricultural area be promoted in accordance with broad plans of national scope, prepared only after a careful survey of the land resources of the nation, and based on the principle of the welfare of the whole people.

Louis A. Bauer and J. P. Ault.

Some Results of the Recent Cruise of the *Carnegie,* 1919-1921.

The magnetic-survey vessel, the *Carnegie,* completed on November 10, 1921, at Washington, D. C., a two-years' cruise, the aggregate length of which was 73,750 statute miles, the second author having been continuously in command.

The general results of the observations made on board the vessel, pertaining to terrestrial magnetism, atmospheric electricity, atmospheric refraction, oceanography, and geography, were set forth briefly and illustrated by lantern slides.

Upon the arrival of the vessel at Balboa, Canal Zone, last October, the first author, as director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, joined the vessel and

remained with her for the balance of the cruise. During the passage from Colon to Washington, special observations and tests were made of the instrumental appliances. It was once more found that with the instrumental appliances and methods used aboard the *Carnegie,* it is possible to determine the magnetic elements at sea, with all requisite accuracy, even during unfavorable conditions of sea.

Concluding tests in Chesapeake Bay again showed the absence of any deviation corrections on board the *Carnegie.*

E. B. Branson (Introduced by H. H. Barrows).

Geography of Eastern Costa Rica.

Eastern Costa Rica is a low lying coastal plain, bounded on the west by volcanic mountains ranging from 2,000 to 11,500 feet in height. The temperature varies little from month to month. The rainfall is rather evenly distributed and averages about 125 inches. The strongest wind is little more than a breeze.

The interior of Costa Rica is in communication with the eastern part only by way of a railroad through the Reventazon valley. The inhabitants and industries of the interior are sharply contrasted with those of the eastern part. The people are about 90 per cent unmixed Spanish, and the main industries are the raising of coffee and sugar cane.

The inhabitants of eastern Costa Rica are about 90 per cent Jamaican negroes, 5 per cent native Costa Ricans and immigrants from other parts of Central America, 3 per cent English, Germans, and Chinese, and 2 per cent Americans.

The chief industry is banana raising, and all the other industries of the region are dependent, directly or indirectly, on bananas.

Banana blight has killed the banana plants in some areas and these have been planted to cocoa or cocoanuts. Sugar cane does not produce well. Experiments in cotton raising have not been successful. Balsa grows rapidly and large numbers of young trees have been set out.

Robert M. Brown.

City Growth and City Advertising.

A discussion of the causes of growth of American cities with an analysis of the 100 cities showing the largest percentage of gain since 1910. An attempt is made to classify by types the advertising campaigns of cities, to indicate the economic types and wasteful types, and to correlate advertising with actual increase of population.

O. F. Cook.

Peru as a Center of Domestication.

The primitive civilizations of America were an indigenous development, since they were based on native American plants. The Peruvian

region was the chief center of domestication in America, as shown by the large number of plants that were cultivated, estimated at 70 species. About half of these are strictly endemic species, grown mostly at the higher altitudes, while the cultivated plants of the lower valleys of Peru were also the chief basis of agriculture in other parts of America. A study of the native names of cultivated plants in Peru indicates that all of the principal lowland crop plants of other regions were known to the ancient Peruvians before the Spanish conquest. Not only maize, beans, squashes, peppers and peanuts, but cassava, sweet potatoes, yautias and several other root-crops were grown in the Peruvian region, and may have originated there. A list of the native plant names and other facts indicate a primary development of agriculture in the Peruvian region. Only a few plants were cultivated in other parts of America, but not known in Peru, the principal examples being cacao in Central America and the pulque agave in the tablelands of Mexico. These domestications appear strictly secondary and incidental to the use of maize as the principal crop.

W. M. Davis.

The Barrier Reef of Tagula, New Guinea—Printed in full herewith.

Nevin M. Fenneman. (By permission of the Director of the U. S. Geological Survey.)

Certain Features of Arid Region Topography.

Tendency of gullies of drains to expand with flat bottoms, vertical sides and no tributaries. Reasons for this tendency. Its relation to wider spread horizontal stripping with little or no down cutting. Production of vertical sided mesas and reasons for coarse texture drainage pattern on semi-arid plains.

A proposed Alteration in the Physiographic Map of the United States.

J. Paul Goode.

The American Need for Authority on Fixing the Form of Foreign Geographic Names.

E. S. Gregg (By Invitation of Council).

The Influence of Geographic Factors on Ocean Shipping.

The distribution of natural resources and the state of economic development of a country determine the volume and the character of its trade, and consequently, its steamship services. The United States is rich in natural resources and has reached a high state of industrial development. As a result, the outward volume of its trade is three times the inward volume, if bulk oil, which moves in specialized vessels, is excluded. An analysis shows the imports exclusive of oil and exports

exclusive of coal, grain, cotton, and lumber make a fairly well-balanced trade; which points to the conclusion that the United States does not need a merchant marine large enough to carry 50 per cent of its total trade, but 50 per cent of its manufactured and semi-manufactured articles. A study of the leading maritime countries shows that a country rich in natural resources does not develop a large merchant marine because exploiting its natural resources is more profitable than performing an international service such as shipping. On the other hand, countries meagerly endowed with natural resources are forced into foreign trade and collateral services.

Roland M. Harper.

Some Regions in the United States with Stationary Population.

About one-tenth of the inhabitants of the United States are living in counties whose total population has been practically at a standstill for 25 years or more, in some cases for over 100 years. Although nearly every state has one or more such counties, they are not scattered fortuitously, but are mostly aggregated in certain natural regions. A statistical study of these regions shows that most of them have from 30 to 60 (never more than 90) inhabitants per square mile, and are characterized by fertile soils and extensive farming, with rather low yields per acre but high standards of living. The significance of this state of affairs and the advantages of residence in such regions were briefly discussed.

George D. Hubbard.

Geographic Setting of Chengtu, China.

Chengtu, a city of 600,000 to 800,000 people, is located on the rich, constantly renewed agricultural plain near the lofty youthful mountains of western Szechuan. It is over 650 miles to the nearest coast, and over 1500 miles by river to Shanghai, the port its products to other countries must use. It is 1000 miles from Hankow, the best point to reach a railroad.

Its only wheel commerce and travel are on wheelbarrows. Boats on streams and canals carry much. The real commerce is carried on poles slung on the shoulders of men.

The very fertile plain is greatly benefited by the ancient flood-control and irrigation system made possible by using the mountain streams that have built up the plain which the city occupies.

Mineral resources of the plain are soils, clays, and sands; of the bordering mountains, are lime and cement rock, coal, iron, oil, gas, marble, granite, copper, lead, zinc, silver, and gold.

By virtue of its position in the midst of the plain and the mountains with their wealth and possibilities, Chengtu is an important commer-

cial collecting and distributing point, a growing industrial city, a center of learning and art. With the coming of the railroads over her old foot-worn paths, and the modern development of surrounding resources, she will be the greatest city in all West China.

W. L. G. Joerg.

Some Observations on the Present Status of Geography in Western and Central Europe.

The paper was based on observations made in 1921, while on six months' leave of absence granted by the American Geographical Society, and ten to twelve years before, during a prior sojourn in Europe, as well as on printed sources of information. The territory covered on these two occasions included Great Britain, France, Germany, Denmark, Belgium, Holland, Switzerland, Austria, Bohemia, Hungary, Italy, and Spain. Other countries of Europe, outside of Russia and the Balkan States, were also discussed, on the basis of printed information. The paper dealt mainly with the development and status of geography at the universities and present tendencies in the subject. It has appeared in the April, 1922, *Geographical Review*.

Douglas W. Johnson.

The Battles of the Ourcq and Marne in 1814 and 1914—Read by Title.

The extent to which topography may influence military strategy and tactics is strikingly illustrated by a comparison of certain phases of Napoleon's 1814 campaign with the Allied operations of September, 1914, and later. On the same terrain there were fought, one hundred years apart in time, Battles of the Ourcq and Battles of the Marne. In both battles of the Ourcq the Germans attempted to turn the French left, and in both cases the attempt failed. In both Battles of the Marne the Germans held their opponents at bay along that barrier for a time, but in both cases the obstacle was eventually forced. Thereupon the Germans in both cases fell back behind the Aisne barrier and later fought a battle on the heights of the Chemin des Dames. There the same terrain imposed the same manoeuvers upon the contending armies to an extent which must profoundly impress the student of military geography.

Neil M. Judd (Introduced by invitation).

The National Geographic Society's Pueblo Bonito Expedition.

Pueblo Bonito is a prehistoric ruin, perhaps 1000 years old, situated in the semi-desert region of northwestern New Mexico. It is more than three acres in area. There were about 300 rooms on its ground floor; its walls were at least four stories high. Its dwellings were terraced

upward from two inner courts bordering which were 20 or more kivas —rooms utilized both as council chambers and as religious sanctuaries. The archaeology of Pueblo Bonito shows it to have been occupied throughout a considerable period, during which groups came in from other settlements to join with the Bonitians. As a result of these immigrations, culture phases distinguishable from those native to Pueblo Bonito were introduced. The Bonitians were familiar with distant peoples for, among other trade objects, they obtained shells for ornaments from the Pacific coast and live macaws (*Ara macao*) from the Valley of Mexico. They were essentially agriculturists and tilled large fields of corn, beans, squash, etc. No trace of their distinctive culture has been found elsewhere but it is to be expected that the present explorations of the National Geographic Society will connect the ancient Bonitians with other peoples who dwelt in the great plateau region of the southwestern United States in prehistoric time.

Julius Klein (Introduced by George B. Roorbach).

Geography in the Bureau of Foreign and Domestic Commerce.

C. F. Marbut.

The Soil Geography of the Northern Great Plains.

Character of the Soils of the Great Plains. Their distribution and relations to topographic, geologic, climatic, agricultural and population features. A definition of the Great Plains and of the Northern Great Plains from the point of view of Soil Character.

A Soil Map of the United States.

Exhibition and brief description of a new soil map of the United States, being prepared by the U. S. Soil Survey.

F. E. Matthes.

The Evolution of the Stepped Canyon Profile of Glaciation.

George J. Miller.

Twenty-five Years' Growth in Collegiate Geography.

To ascertain the growth in geographic education that had taken place in America during the past 25 years, data concerning collegiate geography were secured from 369 higher educational institutions. For this purpose a year's work was defined as geographic instruction extending through four or five hours weekly, for a school year. This was considered a better measure of growth than the increase in the *number* of courses and also of greater significance.

Twenty-five years ago the institutions reporting offered a total of 31 years of collegiate geography, including all duplications of the same or similar courses. Today 338.37 years, or an increase of 991.5 per

cent, are offered. The work in universities and colleges has grown from 11.25 years to 177.56 years, an increase of 1478.4 per cent, and in normal schools (now generally known as teachers colleges) from 19.95 years to 159.58 years, or an increase of 699.9 per cent. The relative decline in normal schools is of vital significance to those interested in elementary and secondary school geography teaching.

Wisconsin leads among the states with an offering of 34.95 years; Illinois is a close second with 34.83 years; New York is third with 33.1 years, and Ohio is fourth with 32.3. Further data from these states would probably change their rank, but they would remain at the head of the list, as Massachusetts, Pennsylvania, and Michigan rank next in order with about one-half the offering.

The leading institutions are the University of Chicago, Columbia University, and the University of Wisconsin. At least 15 years of consecutive work may be taken in the first-named institution. Eight other universities and six normal schools offer four to six and one-half years of collegiate geography.

Data recently collected by a committee of the National Council of Geography Teachers indicate that graduates of normal schools are yet very inadequately prepared to teach geography in the elementary and secondary schools. As these schools prepare most of such teachers this deficiency should be removed at the earliest date possible.

These data, from 75 normal schools distributed through 32 states, show that out of 5497 recent graduates 15.7 per cent had no geography in the normal school; 29.4 per cent had one 12-week course; 24.9 per cent had one 18-week course; 17.7 per cent had 24 weeks. 6.8 per cent had 36 weeks, and only 5.4 per cent had more than one year of geography. This is of vital significance owing to the fact that only a small percentage of these students have had any geography since they left the seventh grade, while nearly all of them will go out to teach the subject. If these same teachers had received no more training in history, mathematics, or English, these subjects would be as poorly taught and school administrators would demand immediate reform.

A. E. Parkins.

Topographic Types about Nashville (Illustrated)—Read by Title.

A study in response to types of topography in the Nashville region. About Nashville there are three strongly contrasted types of topography, the basin, the ridge and valley, and the highland.

G. T. Rude (Introduced by William Bowie).

Shore Changes at Cape Hatteras—Printed in full herewith.

C. S. Scofield.

Limitations of Irrigated Agriculture.

H. L. Shantz.

Urundi.

Urundi lies north and east of Lake Tanganyika. It was previously a part of German East Africa, but is now under a mandate exercised by the Belgian King. The country consists of an upland with rounded mountains, ridges and valleys. It is a rich grassland, excellent grazing country, supporting many cattle and a dense population of agriculturists. The dominant tribe is Hamitic, and almost entirely free from the influence of European civilization. The principal exports are palm oil, butter, beans, and hides.

J. Russell Smith.

The Division of North America into Economic Regions.

A Lantern Slide Map of North America was presented, showing a proposed division into regions.

H. N. Whitford.

The Climatic and Economic Relations of the Forests of Torrid and Temperate Zones.

Brief discussion of three classes of climate. Climatic conditions of three great forest regions; viz., Amazonian Evergreen Hardwood Forests, Pacific Northwest Coniferous Forests, and Deciduous Forests of Eastern United States. Comparison of these forests from climatic standpoint. Brief discussion of past climates in their relation to these classes of forests. The power of each class of climate to store up energy in the form of wood. This is expressed by the ratio of 1:2:4, that is, one stands for deciduous forests of temperate regions; two for coniferous forests of Pacific Northwest; and four, for the Amazonian forests. Significance of this relation for growing crops of timber. Present and future relations of the three classes of forests to furnish materials for economic use.

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GEOGRAPHY AS HUMAN ECOLOGY.*

HARLAN H. BARROWS

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GEOGRAPHY AS THE MOTHER OF SCIENCES.—Only in recent years has geography been recognized to any extent in America as an appropriate subject for university instruction and research, as a science with vital truths to contribute to human knowledge, and as an art having wide application to practical affairs. One is not surprised, therefore, to hear it frequently characterized as the youngest of the subjects of advanced study. It is of course unnecessary to remind this audience that geography, on the contrary, properly can claim the title of Mother of the Sciences. Centuries before Christ it was a recognized study whose field embraced the entire universe. As time passed, geography bore many children, among them astronomy, botany, zoology, geology, meteorology, archæology, and anthropology. Some of its offspring have pursued independent careers in the world of science for so long a time that, quite naturally, their relation to the mother subject commonly is entirely overlooked. Each attained its independence by taking over a part of the parental estate whose cultivation involved distinctive tasks and by working it more intensively than the parent had done. Thus each child became a successful specialist, while the parent, though it relinquished most of its original domain and many of its earlier functions, still retained multifarious interests. Moreover, geography re-

*Presidential address before the Association of American Geographers, Ann Arbor Meeting, December 1922

peatedly has undertaken new obligations as marginal fields have become new centers for research, and so has added to the complexity and extent of its domain. In other words, its boundaries expanded in some quarters, even as they contracted in others. Thus the scope of geography has changed from time to time in the past, and future changes may be anticipated with confidence. Geography perhaps will remain for many years a "vibrant science."

Under such circumstances it doubtless is inevitable that divergent opinions should obtain concerning the content and scope of geography, and that questions should arise concerning the future of the subject. Discussion of these matters is by no means confined to America, as some have appeared to think. For example, Hogarth, in the course of his Presidential Address last year to Section E of the British Association, said: "Ever losing sections of her original field and functions, ever adding new sections to them, geography can hardly help suggesting doubts to others and even to herself. There must be a certain indefiniteness about a field on whose edges specialisms are forever developing towards a point at which they will break away to grow alone into new sciences. The mother holds on awhile to the child, sharing its activities, loath to let go, perhaps even a little jealous of its growing independence. It has not been easy to say at any given moment where geography's functions have ended and those of, say, geology or ethnology have begun. Moreover, it is inevitably asked about this fissiparous science from which function after function has detached itself to lead life apart—what, if the process continues, as it shows every sign of doing, will be left to geography later or sooner? Will it not split up among divers specialisms, and become in time a venerable memory?" Though they have been discussed in various quarters, such questions perhaps have nowhere received more attention of late than in this country. The members of this Association will recall especially the Presidential Address of Fenneman, in which he asked the question, "Suppose geography were dead, what would be left?" and proceeded to consider a possible partition of geography's domain. Hogarth, Fenneman, and, so far as I know, all other competent geographers who have spoken on the subject, assure us that there is no possibility that geography will be moribund, because it has a necessary and distinctive task to perform which other sciences cannot discharge. Doubtless all geographers concur in this view, but quite as certainly there is disagreement among them as to the precise nature of the distinctive task in question. Geography is not at all peculiar, as sometimes suggested, in that the twilight zone by which it is bounded is both vague and unstable. This is true also of geology, botany, economics, history, sociology, and various other subjects. But it per-

haps is peculiar in that radical differences of opinion exist among its exponents concerning its *distinctive functions,* concerning its *center*—to borrow Fenneman's figure of four years ago.

HUMAN ECOLOGY AS THE UNIQUE FIELD OF GEOGRAPHY—What then, is the concept that marks out a distinctive field for geography? The answer to this question is foreshadowed, it seems to me, by recent tendencies in geographic work in various European countries, notably in France and Great Britain, and especially by developments in America. The rise of what we are pleased to call modern scientific American geography has occurred within scarcely more than a quarter of a century. It began with the brilliant work of Davis, Gilbert, and a few others in physiography,—or in physical geography, as it sometimes was called. It is a singular fact, which may be recalled in passing, that geography, though it is the mother of geology, has, in the recent period which has witnessed its revival in America as a subject of higher study, been fostered by geology. In one university after another work in geography has been offered first in the Department of Geology. As this work increased, the official title of the department in not a few cases was changed to "The Department of Geology and Geography." This is the status of things now in seven or eight of the leading universities of the Interior. Scarcely was physical geography established, or perhaps I should say rejuvenated and reestablished, before an insistent demand arose that it be "humanized." This demand met with a prompt response, and the center of gravity within the geographic field has shifted steadily from the extreme physical side toward the human side, until geographers in increasing numbers define their subject as dealing solely with the mutual relations between man and his natural environment. By "natural environment" they of course mean the combined physical and biological environments.

Thus defined, geography is the science of *human ecology.* The implications of the term "human ecology" make evident at once what I believe will be in future the objective of geographic inquiry. Geography will aim to make clear the relationships existing between natural environments and the distribution and activities of man. Geographers will, I think, be wise to view this problem in general from the standpoint of man's adjustment to environment, rather than from that of environmental influence. The former approach is more likely to result in the recognition and proper valuation of all the factors involved, and especially to minimize the danger of assigning to the environmental factors a determinative influence which they do not exert.

It has been said by some that though the foregoing definitional statements indicate a field for human ecology, they cannot do so for geography because the latter term has a fixed connotation. Quite the

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contrary. If the history of geography teaches one lesson more clearly than another, it is that the etymology of the word has not delimited the field to which it applies. In the future, just as in the past, the scope of geography will be determined largely by that of the constructive work of its followers and by the labors of men in kindred fields.

THE RELATION OF GEOGRAPHY TO OTHER SUBJECTS.—The conception of geography as human ecology would, it seems to me, help materially to dispose of the much-discussed problem of its alleged overlap with certain other subjects. In order to show the interactions between man and a particular environmental complex, geography would, of course, deal with the various elements of the complex—with land forms, soils, climate, vegetation, and so on through the familiar list. It would not, however, be the business of geography to explain the origin, character, and occurrence of these environmental features, nor their relations one to another, but to examine the responses of man to them, considered individually and in combination. Let me be more explicit. Physiography, as an abstract study of the evolution of land forms, has been claimed for geology, whereas regional physiography has been held by some to be a part of geography. It never has been clear to my mind that a body of facts and principles is shifted from one science to another *merely* by giving it areal application. In any event, geography defined as human ecology would not be concerned with the genesis and development of land forms in particular areas or in general, but with the adjustments of man to land forms as elements of the natural environment. In other words, the interests of geology and geography in land forms would be mutually exclusive. In a similar way, geography as human ecology would not be concerned with an explanation of the character and distribution of the different climates of the world, but with the human relations of climate, commonly as one element merely of an environmental complex. Again, geography would not deal with the relations of plants and animals to their physical environment, but with plants and animals as elements of the natural environment affecting man. In short, geography treated as human ecology will not cling to the peripheral specialisms to which reference has been made—to physiography, climatology, plant ecology, and animal ecology—but will relinquish them gladly to geology, meteorology, botany, and zoology, or to careers as independent sciences.

It may be well explicitly to state at this point what already has been implied. Title to any of these fields can be established only by their successful cultivation, and for the most part productive research in them is not being carried on by geographers. The foregoing statements are not intended for the briefest moment to imply that the geographer will not need a technical knowledge of those environmental features,

the origin, character, and occurrence of which are explained by these other sciences. On the contrary such a knowledge is an indispensable prerequisite to successful geographic work. It may be added, however, that in some cases the treatment of these environmental features by other sciences is not of the type that best fits the needs of the geographer. Physiography, for example, seemingly has failed to produce a classification of certain land forms suitable for geographic purposes.

In considering the external relations of geography, most attention has, I think, been given by American geographers to its points of contact with the physical and biological sciences to which reference has just been made. This has been a natural result of the history of the subject in this country. In the immediate future, however, increasing attention doubtless will be given to its relations to the social sciences. It is not our province to attempt to define these sciences with exactitude —this is a task which the social scientists themselves apparently have not accomplished to their mutual satisfaction—but it is essential that we try to differentiate these fields from geography, and so it is necessary that we form, if possible, a clear conception of the particular phase of human affairs to which each one gives a unique or dominant attention. What is the particular point of view from which economics, history, sociology, and political science deal with the development of man and his civilization, with the complex and interrelated aspects of human activity?

The unique problem of the economists apparently is the analysis of the economic structure of society and the formulation of economic generalizations or laws for the guidance of individuals and groups. Thus economics considers the activities that man pursues in appropriating or adapting natural resources to his material wants with a view especially to understanding those institutions and processes of society which these activities have induced, and by which in turn they are in part conditioned. In short, economics seeks to explain certain relations among men, relations many of which arise from man's utilization of the resources of the earth, while geography seeks to explain certain relations between man and the earth.

Some historians assert that the aim of history is to portray and explain the whole development of civilization. One perhaps need not quarrel with this program for history, which would deny to the other social sciences and to geography their separate fields, for it assuredly will remain an unattainable ideal. The historian cannot explain everything, however great his ambition may be. Scientific history is concerned with tracing the evolutionary development through the ages, of specific social groups, institutions, movements, and ideas. History, therefore, deals largely with the past. Geography proper deals

largely with the present. Historical inquiry begins with the fragmentary records of man recoverable from the dim mists of antiquity; geographical inquiry finds its most effective point of departure, as Brunhes has urged, with those surface manifestations of man's present occupation of the earth which make up the cultural landscape. The historian, in other words, begins his studies with what our remote ancestors saw; the geographer begins with what we ourselves see. History is concerned with *time* relations; chronology is its organizing principle. Geography is concerned with *place* relations; ecology may well be its organizing concept. History and geography therefore deal with human affairs from contrasted view points, employ dissimilar methods, and arrive at generalizations of a different nature.

Sociologists have found it peculiarly difficult to define a distinctive field for their subject, and yet the contributions of sociology to knowledge have been of the first order of importance. Like history, it traces and helps to explain the processes and the progress of social development. In so doing, however, it deals, in contrast with history, largely with *types* of social organizations and of social institutions. It analyzes the relations of man to man, of man to group, of group to man, and of group to group with a view to disclosing the existence and operation of laws of association. In so doing it deals, for example, not with particular individuals, but with any individual at a given stage of development. It analyzes social development, characterizes in generalized terms the processes concerned in it, and defines the stages involved, all in such a way that its findings function vitally in the historical interpretation of the social development of any given group of people. Thus history becomes, in a measure, *applied* sociology. Sociology also seeks to provide a technique for the study of contemporary social life, and through such study to develop principles for the guidance of social service. While sociology has given some attention to the relation of society to the natural environment, especially in connection with social origins as expressed in the life of primitive people, this branch of human ecology has not been systematically studied, nor can it be until both geography and sociology have made further progress. Whether this work will be done chiefly by geographers or by sociologists is not apparent. Evidently sociology always will deal very largely with cultural relations among men, that is to say with the social environment of man, and this clearly differentiates the center of its field from that of geography.

Political science perhaps has the most sharply defined field of the social sciences. It deals with the political structure of society, with the regulation, restraint, and promotion of human activity through law and governmental action, and seeks to give an understanding of the

principles that underlie all the functions of government. It has to do exclusively with the political environment of man, and so is set apart from geography.

Geography finds in human ecology, then, a field cultivated but little by any or all of the other natural and social sciences. Thus limited in scope it has a unity otherwise lacking, and a point of view unique among the sciences which deal with humanity. Through a comparative study of human adjustment to specific natural environments, certain reliable generalizations or principles have been worked out, while many others have been suggested tentatively. These are the requisites of any science: a distinctive field, and a controlling point of view by means of which its data may be organized with reference to the discovery of general truths or principles.

THE DIVISIONS OF SYSTEMATIC GEOGRAPHY.—If geography be regarded as human ecology, three major systematic divisions of the subject are at once to be recognized, namely economic geography, political geography, and social geography, corresponding to the three great types of human activity that are related to the earth.

According to this scheme, economic geography would seek to account for those adjustments of man to his environment which are associated with the getting of a living. Among its subdivisions would be agricultural geography, pastoral geography, the geography of extractive industries (mining, logging, fishing, etc.), commercial geography, and the geography of manufacturing. Economic geography is the best developed division of the subject, doubtless because most of the activities with which the economic geographer is concerned involve the direct utilization of earth resources and result in various readily discernible surface features which help to make up the cultural landscape. Economic geography also is the most fundamental division of the subject.

If geography as a whole be regarded as human ecology, the viewpoint of political geography follows as a matter of course. It aims to account for such relationships as may exist between man's political attitudes, activities, and institutions, on the one hand, and the natural environment on the other. Such connections must be established in most cases through the facts of economic geography, and not directly. Failure to recognize this, and to proceed accordingly, invites untenable generalizations and helps to make much so-called political geography really political history, with at best a geographic slant.

Theoretically at least there is a definite field for social geography, which would study the connections that may exist between the social life of peoples and their natural environments. But the facts of "living" are intangible and for the most part find any connections which

they may have with the natural environment through the facts involved in "getting a living." As already suggested in connection with sociology, this body of relationships appears to form a potential field for geography rather than an assured field.

Regional Geography.—We come now to regional geography, properly recognized as the culminating branch of the science because it involves facts and principles from all the divisions and subdivisions of systematic geography. As you would expect from the statements already made, I believe that regional geography, even in its widest sense, properly is concerned only with the mutual relations between men and the natural environments of the regions or areas in which they live. I realize fully that here again I depart widely from the viewpoint of most geographers. It has been pointed out that any environmental element (topography, soil, climate, vegetation, etc.) can be studied with reference to the facts and causes of its distribution and it has been urged that such a treatment is the function of regional geography. Does the world of science look to geography for this service? Does not geology, for example, explain the distribution of volcanoes, and zoology that of fishes? Could *any* one science hope really to explain the distribution of all the phenomena of the earth's surface with which science in general is concerned? Are not the technical methods of inquiry too diverse and the field too vast? How much would the other sciences know about the causation of the distributions with which they deal if they had waited upon geography for the information? How *can* certain geographers seriously "claim for geography to the exclusion of any other science, all study of spatial distribution on the earth's surface"? Again it is urged that in any event regional geography comes into its own when the synthetic element is introduced, and the different items are studied in the light of their interactions upon one another. Proponents of this view hold, moreover, that such a study of inter-relationships in an uninhabited area would still be of the essence of geography. It does not seem to me, however, that geography has any function to perform in connection with such studies of non-human relationships. All the more significant interactions of the natural surface elements are considered by other sciences without recourse to geography. Thus physiography considers the influence of vegetation on the development of land forms, and botany takes account of the effect on plant life of topography, soil, and climate. A consideration of an uninhabited region gains geographic quality, as it seems to me, only when the environmental elements there existing are considered, particularly in conjunction, from the standpoint of the advantages and disadvantages of the region for human occupation and use. Even though the en-

vironmental conditions of a region preclude human habitation, it may be studied profitably from the viewpoint of the human ecologist. The thesis I am trying to maintain is that a regional treatment has geographic quality only when the governing concept throughout is human ecology. The usual treatment has chapters on physiography, climatology, botany, economics, history, etc., and though each has a special unity in itself, there is no scientific unity to the whole and certainly no geographic concept which prevails throughout, so that, as noted by one of my predecessors in this chair, entire chapters might be transferred bodily to monographs, for example, on economics or history. The possibility of such transfer stamps the treatment as non-geographical. Doubtless there will be a demand for scholarly treatises on many regions which will present all that is known of significance about the regions, but let us not call all such diversified information geography, or suppose that it can be provided by geographers alone or by the followers of any other single science. Fenneman has told us that "the center of geography is the study of areas." Even an extended study of an area need not, however, involve any real geography. I should like, accordingly, to suggest as a substitute the idea that "the center of geography is the study of human ecology in specific areas." This notion alone holds out to regional geography a distinctive field, an organizing concept throughout, and the opportunity to develop a unique group of underlying principles.

Two basic problems in economic regional geography, problems closely related to each other but yet distinct, are (1) how does man use the land and its resources, and why does he use them as he does? and (2) what are the advantages and disadvantages, the opportunities and handicaps, of the region for utilization by man? The first problem involves an interpretation of existing economic adjustments; the solution of the second one provides a basis for more effective adjustments. An investigation of the first problem begins naturally with an examination of the surface manifestations of man's occupation of the region, that is with a study of the features of the cultural landscape. No other science, it may be noted in passing, gives systematic attention to the development of the cultural landscape.

The detailed and authoritative treatment of these problems requires field work, especially the preparation of maps showing the present utilization of the land, the highest utility of the land, and the distribution of all significant cultural features. Some of these features are not mapped by other field workers, while others, though mapped, are not treated in a manner suitable for geographic purposes. Neither of these basic problems can be solved in terms of natural factors alone, and the geographer should be very cautious not to attach

undue weight to such factors. The habits and aptitudes of the people, markets for their products, prices, transportation facilities and rates, land values, the availability and cost of labor, the competition of other regions, laws and governmental policy—all these and various other factors may help to bring about a particular adjustment to environment. The solution of the geographic problem requires the use of these psychological, economic, political, and other facts. So used, they take on a geographic quality, just as geographic facts, when used in certain ways, acquire the character, for example, of economical or historical items. No science enjoys exclusive possession of all the data with which it deals, and whether a given fact is geographic or not may well depend, it seems to me, on how it is used. Detailed regional studies of the kind to which I have referred are needed almost everywhere; not alone in the newer lands in which an incoming population is seeking adjustment, but quite as much in older areas, where, in some cases, the people are out of adjustment to their environment. They are needed also in areas devoted chiefly to manufacturing no less than in areas used for farming or grazing, and in the former they require a special order of skill, for where the industrial structure of a community is complex, its environmental contacts are likely to be involved and obscure. Detailed field studies in the economic geography of restricted areas will form, I believe, the chief road to further advancement of our science. Especially will they in time establish a firmer foundation for fruitful studies in the more or less nebulous realms of the political and social geography of specific regions.

Urban Geography.—Urban geography really is a phase of regional geography, and studies of individual cities may be prosecuted no less advantageously than those of other areas from the viewpoint of human ecology. Two fundamental problems in the geography of any city will sufficiently illustrate this method of attack: (1) The interpretation of the city landscape, which is simply a special type of cultural landscape. In this connection one should consider such things as the structure or ground plan of the city; its street pattern; the location of its transportation lines; the distribution and character of its manufacturing; wholesale, retail, residential, tenement, and other districts; and the location of its parks and other open areas. To account for the use of land in these different ways within a city area is as truly geographic as to account for the use of land for different crops in a rural district. (2) An appraisal of the present activities and the prospects of the city in the light of its environment. Its stage of development, the advantages and disadvantages of its site and situation, its relations to supporting lands and to rival urban centers: these are some of the factors that must be taken into account in making the valuation.

Historical Geography.—I can best make clear my views concerning the scope and relations of historical geography, the remaining branch of the subject according to the scheme here suggested, by reference to my own experience in that field. One of the courses in history which I took as a student dealt chiefly with the expansion of the American people. It stressed the social, political, and economic conditions of the great movement across the continent from the Atlantic seaboard to the shores of the Pacific, but occasional references, of absorbing interest to me, were made to the more obvious geographic relations that were involved, such as the influences of land forms and of waterways. This course, perhaps more than any other single influence, led me later to undertake the development of a group of courses in Geography dealing somewhat systematically with the relations between earth conditions and earth resources, on the one hand, and the settlement and development of the country on the other. In connection with this work I came to realize that American history, on its material side, fundamentally is largely a record of the adjustments of a rapidly expanding people to varied environments. I also realized in time that in almost any unit area of the country one may trace a continuous evolution of the environmental relationships of the people. It would be a great mistake to suppose that in the course of these ever-shifing relationships the natural environment has remained unaltered; that, as some have put it, the natural factor is the constant, and the human factor alone the variable. An environmental complex may be changed profoundly, even in a short interval of time, by the operation of natural forces and especially by the activities of man. Even though its physical aspect changes but slowly, its economic utility may change repeatedly and greatly for many reasons, such as the discovery of mineral wealth, the application of new methods of land utilization, improved transportation, and altered relations to other regions—to mention only a few causes. More and more I have come to feel, as a result of this work on the United States, that it is the special task of the historical geographer to describe and so far as possible to explain this evolution of man's environmental relations. To me, indeed, historical geography has come to mean simply the geography of the past,—human ecology in past times. Unstead also recently characterized historical geography as "the geography of the past," but to him this phrase has a broader meaning, as he would not restrict geography to human ecology. Historical geography, the geography of the past, helps to show the significance of past geographic conditions in the interpretation of present-day geographic conditions. It provides the key to many environmental relationships that have persisted after the occasion for them has passed. It introduces, so to speak, the "third dimension"

into geography. It helps us to see that the present adjustments of people to their environments represent only a stage in a ceaseless process of evolution, and it throws some light on the changes that are before us. By helping to teach that no adjustment of man to the earth is permanent, that the only permanent thing is change, it answers, by the way, one phase of that oft-repeated question about the future of geography. Some eminent geographers, though they assign to geography a wider scope than here advocated, imply that when at last the explanatory description of the earth shall be completed the task of geography will be finished. On the contrary it will come to an end only if and when human life disappears from the earth.

Historical geography deals chiefly with the *past* and with the *evolution in time* of those phenomena which it treats, and so partakes of the distinctive characteristics of history. It restricts its attention to man's relation to his environment, and so is altogether human ecology. It has thus the distinctive qualities of both geography and history.

Just as I formerly encouraged my students to begin their treatment of a region in all cases with an explanatory description of its physical features, one after another, so I encouraged them, when at last they came to a consideration of man, to start invariably with the earliest settlement of the region, and trace, step by step, the development of its human geography. I now believe that in all cases we should begin with the consideration of man's environmental relations, and proceed to their analysis, classification, and interpretation; that in studies in geography proper we should begin with *present day relations,* and invoke the past only when necessary in order to interpret the present; and that in studies in historical geography we should begin with the *relations of the earliest stage of adjustment* and then consider those of successive stages, each in turn.

THE INDEFINITE BOUNDARY ZONE.—Since the different phases of human activity are connected with one another organically, all facts relating to the life of a community may be said to have a near or remote geographic significance. This constitutes, I believe, a real menace to the further development of geography in an orderly and scientific manner. As in recent years we have stressed increasingly the study of man, there has arisen a real danger that all sorts of human facts will be claimed for geography without the establishment of any relationship to the earth. Illustrations of this tendency need not be cited, for it must have been apparent to all thoughtful observers. It is not the human fact which is geography, any more than it is the environmental fact, but rather the relation which may exist between the two. Geography is a science of relationships. I readily agree that in studying the affairs of men from that point of view which is geography, it is

exceedingly difficult to determine where we pass from geography into the social sciences. The boundaries are never lines; at best they are indefinite zones. The more remote applications of earth relations doubtless are very important in many cases and geographers have just as much right to make them as have, for example, the economists or the sociologists. But let us not appear to claim as a constituent part of the domain of geography the remote realms into which we may venture. And especially, as already urged in effect, let us build our approaches carefully and methodically, so as not to leave gaps in the sequence of relationships that will invalidate our conclusions. Let us not, either, claim exclusively for geography functions which it shares with other subjects. The claim recently has been made, for example, that geography alone can give an understanding of the conditions and problems of the peoples of other lands. Certainly this claim cannot promote a sympathetic attitude toward geography on the part of historians, economists and others who know that their subjects also can make highly important contributions along this line. In this particular case let us seek merely to show, through the excellence of our regional studies, that to view the life of nations and of communities in relation to their environments provides one indispensable prerequisite to understanding their problems and their attitudes, and so helps to pave the way for intelligent sympathy and for effective cooperation. The claims to usefulness which geography legitimately can make are sufficiently impressive.

Conclusion.—I may summarize my convictions as follows:

(1) I believe that the age-old subject of geography, though it has lost many specialties, still seeks to cover too much ground, and that it would benefit by frankly relinquishing physiography, climatology, plant ecology, and animal ecology.

(2) I believe that a motivating theme, an organizing concept, is required which shall permeate geography, and give to all its divisions a distinctive point of view. I believe that the problem of the causation of the distribution of surface phenomena, urged by some, and the task of the explanatory description of regions, advocated by others, alike fail to meet this requirement, and that the problem of human ecology may have the vitalizing, unifying influence needed.

(3) I believe that those relationships between man and the earth which result from his efforts to get a living are in general the most direct and intimate; that most other relationships are established through these; that, accordingly, the further development of economic regional geography should be promoted assiduously, and that upon economic geography for the most part the other divisions of the subject must be based.

(4) I believe that geography has been too much a library subject, and too little a field subject. I hold that the field is the geographer's laboratory. I believe that we have made only a beginning in the development of rigorous, scientific methods of field work in geography, as distinct from field work in physiography and geology, and that the development of a thoroughly effective technique in field work is perhaps our greatest immediate need. Since most of us are "rebuilt geologists," do we not, in general, *study* the geological items and merely *observe,* in more or less haphazard fashion, the geographical items? Precisely how should one study in the field those relationships which are truly geographic?

(5) I believe that much of our so-called geographical exposition is something else, that to be truly geographic a discussion must involve from beginning to end an explanatory treatment in orderly sequence of human relationships, and that the development of a satisfactory technique in exposition is only less important than the perfection of field methods.

(6) I believe, finally, in spite of the iconoclastic spirit which may seem to have pervaded my remarks, that we have every reason to congratulate ourselves upon the outlook for geography. It is making remarkable progress in America, though still in a state of flux. By one road or another it will come fully into its own through further experimentation. The road which to me seems most promising is that denoted by human ecology.

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LAWS OF TEMPERATURE*

STEPHEN SARGENT VISHER

CONTENTS

INTRODUCTION.—This treatise is a summary of the temperature aspect of climate only. Concise statements of the ways in which certain aspects of climate differ from place to place are given in some texts and treatises dealing with meteorology and climatology. Similar brief statements of how nature acts have been helpful in advancing many other sciences. These " laws," as they have been termed, call attention to what is known and often reveal the inadequacies of current knowledge. An attempt is here made to state, explain and illustrate what, in lieu of a better short title, may be called " laws of climate." Many of these are obviously not strictly analogous to some of the laws of the more exact sciences, but the term " law of nature " is not applied merely to precise quantitatively demonstrable laws. The aim of this paper is to point out and explain those relations which correspond, in so far as the nature of the subject permits, to the laws of other sciences. Like those laws, these relations are subject to frequent modification, and seldom do they operate in a dominating way. However, neither do many laws of physics, for example, operate except under restricted conditions of temperature, pressure and purity of substance. Many of the laws here given have been expressed or implied

*The laws of wind and moisture will be summarized in a later number.

in one or more of the treatises or texts consulted[1] or in technical papers A number of these laws seem not to have been concisely stated in print, however, and many have not been fully explained. In order to have fewer omissions and more accurate and clearer statements of these laws and their causes, criticisms were obtained from a number of persons. Grateful acknowledgment is here made to all who have so generously assisted in making this study more worth while.*

[1] *Meteorologies:* Davis, (1894), Russell (1895), Waldo (1894) (1896), Moore, J. (1894, 1910), Moore, W. L. (1910), Milham (1912), Hann, Lehrbuch der Meteorologie 3d ed., (1915), McAdie (1917), National Research Council (1918), Shaw Manual of Meteorology, pt. IV, (1919), Humphreys, Physics of the Air (1920); *Physiographies:* Salisbury (1907, 1919) Tarr-Martin (1914); *Miscellaneous:* Ward, Climate (1908, 1918); Hann; Handbook of Climatology (1903); Huntington: The Climatic Factor (1914); Henry and others, Weather Forecasting in the U. S. (1916); Salisbury, Barrows and Tower, Elements of Geography (1912), Shaw and others, Meteorological Glossary (1918); Ferrel, Popular Treatise of Winds (1889); Shaw, Weather Forecasting (1911, 1919); Taylor, Australian Meteorology (1920); *Physics:* Ganot (1905), Watson (1899), Crew (1909), Kimball (1917), Poynting-Thompson (1911).

* C. F. Brooks, Clark University; R. M. Brown, R. I. College for Teachers; C. C. Colby, University of Chicago; E. R. Cumings, Indiana University; W. M. Davis, Harvard University; P. C. Day, U. S. Weather Bureau; C. R. Dryer, Fort Wayne, Ind.; J. Paul Goode, University of Chicago; A. J. Henry, U. S. Weather Bureau; T. C. Hopkins, Syracuse University; W. J. Humphreys, U. S. Weather Bureau; E. Huntington, Yale University; M. M. Leighton, University of Illinois; B. E. Livingston, Johns Hopkins University; W. N. Logan and C. A. Malott, Indiana University; A. McAdie, Blue Hill Observatory; W. J. Milham, Williams College; G. J. Miller, Teachers College, Mankato, Minn.; A. E. Parkins, George Peabody College for Teachers; T. T. Quirke, University of Illinois; R. D. Salisbury, University of Chicago; C. O. Sauer, University of Michigan; H. E. Simpson, University of North Dakota; J. Warren Smith, U. S. Weather Bureau; E. Van Cleef, Ohio State University; O. D. von Engeln, Cornell University; R. DeC. Ward, Harvard University; C. M. Zierer, Indiana University.

LAWS CONCERNING THE HEATING AND COOLING OF THE EARTH

DISTRIBUTION OF HEAT IN POINT OF TIME.—1. *Climate depends upon the nature and effectiveness of solar radiation.*—This is true in so far as temperature and light are concerned, because the great source of heat on the surface of the earth is solar radiation, and also because the amount and type of solar radiation received and retained by the earth varies from time to time. The temperature of any place depends upon various factors, considered in subsequent laws, upon the amount and type of solar radiation and upon the amount of atmospheric and terrestrial absorption. None of these four factors operate at a constant rate in point of time or place. Geographic variations are discussed below. Widespread variations from time to time in the amounts of radiation and absorption are likewise a part of climate. The amount of radiant energy emitted by the sun also varies. A cycle of 11 or 12 years is recognized and there is evidence of both shorter and longer cycles, especially one of about 33 to 35 years.[2] Apparently there are other variations in the amount of energy emitted by the sun within periods of weeks or months.[3] In addition to variations in the amount of solar radiation, there is clear evidence of variation in the type of emanations, as is shown by the intermittent occurrence of auroral displays. Ultraviolet rays also do not always make up the same proportion of the emanations. Long term variations in either the amount or the kind of radiation reaching the earth, even though slight, undoubtedly affect climate in a fundamental way.[4] Sudden changes of pressure of a remarkable type occur over extensive areas and may possibly be due to sudden variations in solar radiation.[5]

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[2] Marvin, C. F.: Theory and Use of the Periodocrite, *Mo. Weather Rev.*, Vol 49, pp. 115-132, esp. p. 131, 1921; Clough, H. W., An approximate seven-year cycle in terrestrial weather with solar correlations, Ibid. Vol. 48, pp. 593-596, 1920; Henry, A. J., Temperature Variations in the U. S. and Elsewhere, Ibid, Vol. 49, pp. 62-70, 1921; Huntington, E., Earth and Sun, 1923; Clayton, H. H., Solar Variation and Weather at Buenos Aires, *Smithsonian Misc. Collect.*, Vol. 71, 1920, and Helland-Hansen and Nansen, Temperature Variations in the North Atlantic Ocean and the Atmosphere, *Smithsonian Misc. Collect.*, Vol. 70, 1920.

[3] Abbot and others, The Solar Constant; *Mo. Weather Rev.*, Vol. 43, p. 212, 1915, and Vol. 47, pp. 1-3, 1919. Concerning the uncertainty of many of the daily variations in the Solar Constant, see Marvin, C. F., Forecasting the weather on short period solar variations, Ibid, Vol. 48, pp. 149-150, 1920.

[4] Huntington, E., The Solar Hypothesis of Climate, *Bull. Geol. Soc. Am.*, Vol 25, 1914, pp. 477-577, and Earth and Sun, 1923; Brooks, C. E. P., The Secular Variations of Climate, *Geogr. Rev.*, Vol. 11, pp. 120-132, 1921.

[5] Huntington, E.: Solar Disturbances and Terrestrial Weather, *Mo. Weather Rev.*, Vol. 46, pp. 123-141, 168-177, 269-277, 1918.

The amount of atmospheric absorption varies with the composition of the air. Changes in the water vapor, CO_2 and dust content of the air are particularly important as these are relatively active absorbers.[6] Water vapor is most important, being almost a full absorber for radiant energy sent out by a black body at a temperature of 212° F.[7] Nitrogen has no known absorptive power and oxygen absorbs only a few wave lengths other than those in the far ultraviolet.[8]

Variations in the amount of water vapor in the air are produced by changes in the temperature of the air and of evaporating surfaces, and in the distribution of land and water, and by variations in wind velocity. Modifications in the distribution of land and water affect climate in many significant ways, but are geologic in origin and are produced slowly. Changes in the average temperature are produced by variations in insolation and in the composition of the air, and by changes in the surface of the earth, and thus in the amount of absorption and retention of radiant energy. It has been suggested that variations in the amount of CO_2 in the air have been due to differences in the temperature of the sea, in which much CO_2 is dissolved; to variations in the activity of volcanoes, which emit much CO_2; and to differences in the rate of depletion of the atmospheric CO_2 by coal-forming plants and by the carbonation of rocks. The rate of depletion is greater when the continents are elevated, as at present, than when they are low and partly submerged, as they have been at many times during geologic history.[9]

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[6] Fowle, F. E., Atmospheric Transparency for Radiation. *Mo. Weather Rev.*, Vol. 42, pp. 2-4, 1914 (a summary of earlier papers by Abbot and Fowle); Dines, W. H., The amount of radiant energy absorbed and reflected by the earth and its atmosphere, *Quart. Journ. Royal Meteorol. Soc.*, April, 1917 (Abstracted in Meteorological Glossary, pp. 331-333; Humphreys, W. J., The Physics of the Air, 1920, (Volcanic dust receives especial consideration). The efficacy of CO_2 as an absorber is discussed in numerous papers. Chamberlin gives a good summary to 1906 in Chamberlin and Salisbury: Geology, Vol. 2, pp. 655-677. See also Clarke, F. W., The Data of Geochemistry, 4th ed., 1920 (*Bull.* 695, *U. S. Geol. Survey*), pp. 49-50, 141-145, and Huntington and Visher, Climatic Changes, their Nature and Causes, pp. 36ff, 19, 139, 1922; also, Kimball, H. H., Variations in the Solar Radiation in the U. S., *Mo. Weather Rev.*, Vol. 47, pp. 769-793, 1919. (The efficacy of water vapor as an absorber is especially emphasized in this comprehensive, detailed paper).

[7] Shaw and others, *Meteorological Glossary*, p. 33, 1918. In the Smithsonian Meteorological Tables, 1918, p. 231, the absorption of different wave-lengths is given. It varies irregularly from 6% to 100% for lengths given out by terrestrial radiation, but for most of the lengths it approaches 100%.

[8] Humphreys, Physics of the Air, p. 81, 1920.

[9] Chamberlin and Salisbury, Geology, Vols. 2 & 3, 1906, as to variation in extent of lands. See also Willis, Salisbury and others, Outlines of Geologic History, 1910, and Schuchert, Paleogeography of North America, *Bull. Geol. Soc. Am.*, Vol. 20, pp. 427-606, 1910; and Pirsson and Schuchert, Textbook of Geology, Vol. 2, 1915.

Long-time oscillations in the amount of atmospheric dust accompany variations in explosive volcanic activity, and changes in the extent of dry land.[10]

Absorption by the earth's surface varies with the distribution of land and water, with the extent and type of soil, rock and vegetation, and with cloudiness and the amount of snow-cover. All of these vary from time to time, and thus help produce climatic changes. The climate of any period, such as that of the present, is affected by all these complex influences, and by others mentioned below. As these conditions vary, climate changes. Climatology comprehensively studied is thus distinctly a dynamic subject instead of a static one.

DISTRIBUTION OF HEAT OVER THE EARTH.—*Effects of Latitude and Altitude. 2. Half of the earth is receiving heat from the sun at any given moment.*—Because of the rotation of the earth, there is a progressive change in the half which is heated by insolation. The amount of heat received per unit of time varies from a maximum in the area where the sun's rays are vertical to a minimum where they are tangent to the earth's surface.[11] Indeed at tangency there is almost no heating due to direct insolation because almost no energy is absorbed and only absorbed energy is effective in raising temperatures. At any given time the rays are nearly vertical (60° or more) over about one-fifteenth of the earth's surface. This proportion receives about 1.2 calories per square centimeter per minute on clear days from direct solar radiation.[12] It likewise receives radiation from atmospheric water and dust which have absorbed or reflect part of the solar radiation.[13] Indeed, in the tropics, one-half of the total energy received is from diffused or reflected

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10 Schuchert, C., Climates of Geologic Time, pp. 265-298 of Huntington's, The Climatic Factor, *Carnegie Institution Publ.* 192, 1914, and (for Dust), Humphreys, loc. cit., pp. 569-603.

11 The intensity of insolation varies with the sine of the sun's altitude. At the equinoxes, it varies as the cosine of the latitude. (Hann, J., Handbook of Climatology, Vol. 1 (tr. by Ward) p. 93, 1903.)

12 63% of 1.92 calories, Abbot, Fowle and Aldrich, The Solar Constant of Radiation. *Mo. Weather Rev.*, Vol. 43, p. 212, 1915. "From March 10 to Sept. 10 the heat received from the sun and sky on clear days on each square meter of horizontal surface (at Washington, D. C.) is equivalent to the energy required to run twenty-five 40-watt electric lamps for 7 hours." (Kimball, H. H., Measurements of Radiation, Ibid, Vol. 43, p. 610, 1915.

13 Dines, W. H., (*Quart. Journ. Royal Meteor. Soc.*, April 1917) estimates that the atmosphere absorbs nearly one-tenth as much solar radiation as does the earth itself. It also absorbs nearly 3/4 of the radiation from the warmed earth and reflects back about 1/10. Only about 1/6 of the terrestrial radiation escapes to space directly.

light.[14] The amounts of radiation (solar and atmospheric) received daily by the earth's surface vary notably with latitude, humidity, and seasons.[15] (See Law 8.)

3. *Normal temperatures decrease with increase in latitude, except just north of the equator, nearly 1° F. for each degree of latitude* (about 1° C. for each 2° of latitude) because insolation diminishes as the angle at which the sun's rays strike the surface of the spherical earth becomes smaller.[16] With this change there is greater reflection, an increase in the area over which a bundle of rays is spread, and of chief importance, an augmentation of the distance which the rays must travel in penetrating the atmosphere. Rays entering the atmosphere at a small angle often are reflected away from the earth. Penetration is also reduced by atmospheric absorption and diffraction or scattering of light rays.*

The average air temperature at the surface of the earth is about 59° F. (15° C.); near the equator it is 80° F. (27° C.) or above, except on the Pacific Ocean where it is about 77° F. (25° C.). The average along the tropics is about 74° F. (23° C.); in mid-latitudes it is perhaps 50° F. (10° C.), and in polar areas 10° F. (12° C.) or less.[17]

In more detail, the mean temperatures are given as follows by Hann:[18] (The Fahrenheit equivalents are given just below the Centigrade figures.)

N. Pole	80°N.	70°N.	60°N.	50°N.	40°N.	30°N.	20°N.	10°N.	Equator.
—20°C.	—17	—10	—1.2	5.8	14	20	25	27	26.6
—4°F.	1	14	30	42	59	68	77	81	80

10°S.	20°S.	30°S.	40°S.	50°S.	60°S.
26°C.	23	18	12	5	—1°C
79°F.	73	64	54	41	30

Were it not for the distribution of heat by winds and ocean currents, tropical temperatures would be much higher and polar temperatures much lower than now, possibly about 131° F. (55° C.) for the equator

[14] Hann, loc. cit., p. 81. See also Very, F. W., Atmospheric Radiation, *Bull. G., U. S. Weather Bureau*, 1900.

[15] Kimball, H. H., Variations in solar radiation in the U. S., *Mo. Weather Rev.*, Vol. 47, pp. 783-784, 1919.

[16] The variation of 1° F. per degree of latitude has been verified in the United States by A. D. Hopkins in his study of the flowering of plants. See "The Bioclimatic Law," *Mo. Weather Rev., Suppl.* 9, 1918, also *Scientific Monthly* 8, 495-513, 1919 and *Mo. Weather Rev.*, Vol. 448, p. 355, 1920.

* See Law 18 beyond.

[17] These figures are from Bartholomew: Physical Atlas, Pt. 3, Meteorology, 1899, as are many similar figures below if not credited to some other source.

[18] Hann, loc. cit., pp. 200-202.

instead of 80° F. (26° C.) and —108° F. (—78° C.) for the poles, instead of about 0° F. (—18° C.) as now.[19]

The decrease in temperature with increase in latitude is not at a uniform rate. It is disturbed by variations in the proportions of land and water, highland and lowland, the amount of water vapor, cloudiness and storminess in the different latitudes, and by differences in ocean currents. On the average the ocean is cooler than the land except in high latitudes where the reverse is true. According to Zenker marine climates are 8.5° C. (15° F.) colder than continental climates at the equator, 7.3° C. (13° F.) colder at latitude 20, 2.3° C. (4° F.) warmer at latitude 40, 8° C. (14° F.) warmer at latitude 60, and 14° C. (25° F.) warmer at latitude 70.[20] Cloudiness generally lowers surface temperatures although it does not do so in winter in some cold regions.[21] Clouds in tropical latitudes reflect, on the average, more than half the solar radiation incident upon them.[22] Investigations in middle latitudes indicate that there is a reflection of 70%.[23] Nevertheless the climate of places in higher latitudes such as the British Isles, which receive much heat from the ocean, are kept mild in winter by being cloud-covered. In such places the effect of the clouds in retarding the escape of heat is more important in winter than is the lessening of insolation which they cause. Storminess increases upward convection, which in turn causes so much heat to be lost by radiation into space that stormy areas and belts tend to be abnormally cool, except in winter in high latitudes. This is in spite of the fact that the cloudiness associated with lows restricts the loss of heat, and the poleward blowing winds bring in much heat.[24]

4. *Normal temperatures fall with increase in altitude about 1° F. for each rise of 330 feet (1° C. for 600 ft. or 183 meters, or .6° C. for 100 meters).* The rate differs somewhat for mountains, plateaus and

19 Salisbury, R. D., Physiography, revised ed., p. 455, 1919.

20 Quoted by Hann, loc. cit., p. 212. In Die Lehrbuch der Meteorologie, 3rd ed., 1915, p. 153, Hann gives Liznar's computations of the probable temperatures of land and water hemispheres at various latitudes.

21 For a good discussion of the lowering of temperatures produced by cloudiness in the lower latitudes (between 30′ N. and 30″ S.) See Huntington: *Bull. Geol. Soc. Am.* 1914, pp. 581-87. The influence of clouds on temperatures in northwestern Europe is discussed in Hann, loc. cit., p. 136.

22 Blair, W. R., *Mo. Weather Rev.*, Vol. 44 p. 194, 1916.

23 Balloon investigations carried on recently by the Smithsonian Institution in southern California, L. B. Aldrich, *Smithsonian Misc. Collect.*, Vol. 69, No. 10, Washington, 1919; Author's Summary reprinted in *Mo. Weather Rev.*, Vol. 47, p. 154, 1919.

24 Huntington, E., *Bull. Geol. Soc. Am.*, Vol. 25, pp. 572-574, 1914.

plains, being 1° F. for each 265 feet of ascent on mountains, 290 feet on plateaus, and 365 feet on plains (1° C. for each 180 meters on mountains, 200 meters on hills and 250 meters on plateaus).[25] For dry "free air" the decrease is 1° F. for each 300 feet (1° C. per 165 meters, or 6° C. per 1,000 meters), on the average, up to the base of the stratosphere, an elevation of about seven miles (11 km.).[26] At an elevation of about 2,000 feet (600 m.) above sea level, the effect of altitude on temperature is appreciable, and at 4,000 feet it is marked, resulting in a short frost-free season in mid-latitudes. Lofty mountains, even in the tropics, have frigid temperatures at their summits, though not a polar climate. The normal decrease in temperature with increase in altitude is due partly to the increased distance from the chief source of atmospheric warmth, the warmed earth, but chiefly to the decreased absorption by the atmosphere of radiation from the sun and of radiation and conduction from the earth. The atmospheric substances which absorb radiation (water vapor, dust and CO_2) all decrease notably in amount with increase in altitude, and as has been remarked, wherever there is little water vapor, CO_2 or dust, there is little absorption. Since radiant energy which is not absorbed does not raise air temperatures, high altitudes cool rapidly and become cold at night, and indeed even during the day, except where the sun is shining upon an absorbing surface. The thinness of the air, with the consequent fewer molecules to scatter the rays, also aids in the escape of heat.* The decrease in nocturnal temperature with increase in altitude is at a greater rate than the decrease in daytime temperatures. The decrease is also at a greater rate on the clear leeward sides of mountains than on the cloud-covered windward sides.[27] This disparity is due in part to the heat liberated at condensation on the windward slopes, and to the effects of foehns on leeward slopes. In the free-air, upward convection helps produce a progressive decline in temperature, since more heat is lost by expansion than is obtained by absorption or conduction. Furthermore, whenever convection is taking place, part of the air at any moderate altitude has recently arrived from a lower altitude. If the rise is rapid, inertia may carry such air far beyond the level of equilibrium and so make it much colder than the surrounding air. However, this condition soon results in a settling of the comparatively

[25] Hann, Lehrbuch der Meteorologic, 3rd, ed., p. 126, 1915.

[26] Humphreys, loc. cit., p. 38.

* See Law 17, beyond.

[27] Hann, Handbook of Climatology, Vol. 1, p. 249, 1903.

dense abnormally cold air to a level where it is neither abnormally dense nor cold.[28]

Effects of Winds and Ocean Currents.

5. *Winds are important in affecting local temperatures, especially along coasts in the higher latitudes, and at night.* Windward coasts in high latitudes are on the average abnormally warm and leeward coasts abnormally cold. Much heat is carried from place to place over the surface of the earth by the winds. In winter many places in high latitudes frequently receive more heat from the wind than by insolation or from the radiation of heat stored up in soil or water. At night there is no insolation and on densely cloudy days in high latitudes, there is but little. When the surface of the ground is cold or snow-covered or the water is ice-covered, they give up only a little heat. The importance of the wind in high latitudes is suggested by the statement that from the poles to latitude 52° the earth's surface receives more heat from atmospheric radiation than by insolation.[29] Even when the sun is shining brightly, a locality may be cold if winds bring in a large body of cold air. Hence the direction of the surface winds often strongly influences the temperature at any place, especially in middle and high latitudes or near the coast.[30] For example, the northeastern part of the United States is remarkably warm in summer partly because southern winds prevail there, while the summers of northwestern Europe are kept comparatively cool by the northwesterly winds prevalent there at that season. Likewise the North Pacific coast of North America has abnormally cold summers partly because strong west or northwest winds from the cold northern Pacific Ocean prevail then.[31]

In the absence of surface air movement, there is little passage of heat by conduction from air to soil, rock or water or in the other direction, because stagnant air has a low thermal conductivity. This is one reason why the surface is hotter on a calm day than on a windy one and why the lower air is colder on a calm night than on a windy one. On windy nights, air cooled by contact with cold ground is soon mixed with warmer air. Thus, although there is more cooling by conduction on a windy night than on a calm one because of the greater contrast between soil and air temperatures, a sufficiently greater quantity of

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[28] For further discussion of this explanation of the vertical decrease in temperature see Humphreys, W. J., A Bundle of Meteorological Paradoxes, *Journ. Wash. Acad. Sci.*, Vol. 10, pp. 153-171, 1920.

[29] Hann, loc. cit., p. 116.

[30] Hann, loc. cit., p. 70, states, "Few districts may be said to have their own climate" because of the importance of winds.

[31] Hann, loc. cit., p. 178.

air is involved so that the temperature of none of it becomes so low as that of the lower air on a calm night.

6. *Ocean currents help to warm windward coasts in high latitudes, and to cool those in low latitudes.*—Much heat is transferred by the movement of sea water. High latitude coasts are usually warmed by heat carried there by the oceanic circulation. Because of the influence of the wind, the agency which transfers the heat from the water to the land, this warming is chiefly felt on the windward coasts. Among the surface currents two may be mentioned: Winds from off the "Gulf Stream Drift" warm northwestern Europe 10° F. (5.5° C.) or more in midwinter.[32] Without its influence navigation would be interfered with by ice that would then accumulate occasionally even in the eastern ports of Great Britain. On the other hand, the Humboldt Current chills the coast of Peru and northern Chile. However, the upwelling cold oceanic waters there, as along other coasts in Trade Wind latitudes, is the chief cause of the coldness of such a current, rather than the rapid movement by the winds of cold water from high latitudes.[33] The active evaporation by the dry Trades is another cause of the coldness, both directly and also by making the surface layers more dense than the fresher but colder water below, which is crowded upward by the sinking of the denser surface water.

Possibly of more significance than surface currents is the deep-sea circulation. All the ocean is surprisingly cold, except the surface, because of the sinking and spread of cold water from high latitudes. The average temperature of the ocean, when all the depths are considered, is less than 40° F. (4° C.). In past geologic ages high latitudes have occasionally been much warmer and more equable than now. Indeed, magnolias and figs have grown in Greenland. If vast quantities of tropical heat were transferred poleward beneath the surface by a reversal of the deep sea circulation, some such mild climate would result.[34] Such a reversal might be produced by a notable increase in the salinity of the ocean especially in low latitudes or by an increase in its temperature especially in high latitudes. The present surface currents from the tropics lose most of their heat by radiation and conduction to the air in low middle latitudes. However, surface currents

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32 Salisbury, loc. cit., p. 470.

33 Hann, loc. cit., pp. 185-187. See also Murray, J., The Ocean, 1912, and Brooks, C. F., Review of papers dealing with climates of Western coasts in the tradewind belt, *Geogr. Rev.* Vol. 11, pp. 633-634, 1921.

34 Chamberlain, T. C., On a possible reversal of deep-sea circulation, *Journ. of Geol.* Vol. 14, pp. 363-373, 1906. See also Visher, S. S. *Bull. Geol. Soc. Am.*, Vol. 32, pp. 429-436, 1921.

may in times past have been more effective in transferring heat poleward than at present. Now, perhaps chiefly because of the retarding influence of cyclonic storms in mid-latitudes, the poleward movement of tropical waters is so slow that comparatively little heat reaches polar regions in this way.[35] If cyclonic storms were far less numerous than now the Westerlies would become more like the Trades in steadiness of direction, and the poleward movement of warm water would be much augmented, thus making possible mild polar climates where the distribution of land and water was favorable.[36] If during the past the deep sea circulation was of the " reversed " type at the same time that the Westerlies were steady at the surface, polar climates would have been especially mild.

7. *Windy places are commonly cooler than less windy ones otherwise similar* because: (1) Wind increases evaporation, and (2) increases the dispersal of local heat by conduction, except when the wind is extraordinarily hot. (3) Much surface wind has recently come from higher latitudes or altitudes and is cooler than the air it displaces. Wherever friction or topographic relations temporarily prevent wind, warm air accumulates whenever heating by insolation is greater than loss of heat by radiation. This is commonly the case in places which receive intense insolation but little heavier air (wind) to force the warm air to rise.* There are three chief exceptions to this law: (1) Areas in middle and especially those in high latitudes are often warmed by wind from the open ocean in winter or from the direction of the equator; hence windy places in high latitudes are often warmer than calm places. (2) Depressions are often cooler during calm nights than on windy ones, because cold air accumulates in depressions during calm nights.† (3) Many places are occasionally warmed by foehn winds.

Effects of Earth's Rotation, Shape and Inclination.

8. *Seasons of temperature occur in middle and high latitudes,* because of the revolution of the earth about the sun and the constant inclination of its axis to the plane of its orbit. As the axis maintains a practically constant direction in space at an angle of about 23½° to

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[35] Helland, Hansen and Nansen, Temperatures of the North Atlantic, *Smithsonian Misc. Collect.*, Vol. 70, #2537, 1920. Huntington and Visher, Climatic Changes, their Nature and Causes, pp. 174-176, 1922.

[36] Huntington and Visher, loc. cit., pp. 166-187.

* See Law 18, beyond.

† Similarly snow-covered surfaces are often cooler on calm nights than on windy ones partly because stagnant air in contact with cold snow cools to a lower temperature than that reached by a mixture of surface air and the warmer aid of moderate altitudes such as obtains on windy nights.

the ecliptic, the northern hemisphere is tipped toward the sun at one time, and six months later, when the earth is in the other side of the orbit, it is tipped away from the sun. The hemisphere tipped toward the sun receives more vertical and nearly vertical rays than the other and hence is warmer. In other words, the north-south shifting of the zone of greatest insolation accompanying the revolution of the inclined earth produces most of our changes of seasons. For example, in the United States, Minnesota receives six times as much radiation per unit area on June 21 as on December 21, and Louisiana two and one-half times as much on June 21 as on December 21. During a year a unit area in Louisiana receives 7 per cent more radiation than one in Minnesota, receiving 36 per cent more in the colder six months but 11 per cent less in the warmer three months. In July, Minnesota receives 20 per cent more than Louisiana. The arid southwest receives almost twice as much radiation as the northeast in winter and nearly 25 per cent more in summer. For example, South Carolina receives only about 75 per cent as much radiation per unit area in a year as does more sunny New Mexico. New Mexico leads each month in the year but more in the colder months and in July than in the other months, because of cloudiness in South Carolina then. The highest average amount received in gram calories per minute per square centimeter is 700 on June 21 in the arid southwest. The lowest is a little less than 100 on December 21 along the northern border and in the Great Lakes region.[37]

Although the earth is nearer the sun and receiving one-fifteenth more insolation in January than in July, the Southern Hemisphere does not receive a greater amount of heat in a year than the Northern. The earth moves with a sufficiently greater velocity along its orbit when nearest the sun as compared with its velocity when farthest away (in July), so that it receives as much heat when it is more than the average distance from the sun as it does when it is less than the average.[38] Indeed, the temperature of the earth as a whole increases from January to July nearly 2.7° F. (1.5° C.) while its distance from the sun is increasing. This is chiefly because of the greater land area in the Northern Hemisphere.[39]

Seasonal changes of temperature have been far less extreme during most of the better known epochs of the geologic past than they are at present. Indeed, freezing temperatures apparently did not prevail even in moderately high latitudes, at least not along the coasts, except during

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[37] Kimball, H. H., cited in note 15.

[38] Hann, loc. cit., pp. 93-101.

[39] Ibid, p. 201.

the several colder or Glacial periods.[40] Students of celestial mechanics insist that there has been no great change in the position or inclination of the earth's axis since the present solar system was organized. It is altogether unlikely that the higher latitudes could have been warmed sufficiently by the escape of heat from the interior of the earth to compensate for the lack of direct insolation in winter. Leading geologists estimate that the earth's interior probably is about as hot now as formerly.* Yet today the escape of heat is normally negligible.[41] In ancient times when high latitudes had a mild climate they must have received the necessary heat through the agency of atmospheric or oceanic circulation. A general "planetary" circulation of the atmosphere like that of the present seems called for by the distribution of insolation. A change in the oceanic circulation appears much more likely than many of the other changes hypothecated. If the ocean were distinctly warm in high latitudes, seasonal changes would be much lessened. The change in the temperature of the ocean might be due to a change in the amount of heat received from the sun or to a change in the amount of heat held in by the atmosphere. The amount held would fluctuate with the composition of the air, with storminess, and with the extent of land and water. Chamberlin[42] has developed the hypothesis advanced earlier by Tyndal, Arrhenius and others, that the alternation of glacial periods and warm climates in high latitudes is chiefly due to fluctuations in the CO_2 content of the air and to accompanying fluctuations of the moisture content. More atmospheric CO_2 would mean a somewhat greater retention of heat and thus more water vapor accompanied by a further increase in heat retention. Huntington[43] reports evidence of a change in storminess and in the location of storm tracks, and points out that heat retention would alter with storminess. Both Chamberlin and Huntington consider modifications in the distribution of land and

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40 Barrell, Joseph: Rhythms and the Measurement of Geologic Time, *Bull. Geol. Soc. Am.*, Vol. 28, pp. 745-904, 1917; citation on p. 827. Schuchert, C.: Climates of Geologic Time in the *Climatic Factor*, pp. 265-298, 1914, Reprinted in *Smithsonian Annual Report*, 1914.

* Chamberlin, T. C., personal communication.

41 The mean temperature of the earth's soil is estimated by Trabert to be raised by conduction from the internal heat of the earth by the trifling amount of 0.1°C. Bowman: Forest Physiography, p. 60, 1911.

42 Briefly stated in Chamberlin and Salisbury: Geology, Vol. 2, pp. 665-667; Vol. 3, pp. 433-436, 1906. However see Clarke: Data of Geochemistry, 4th ed., pp. 142-145, 1920.

43 Huntington: *The Climatic Factor*, Carnegie Institution, 1914; and The Solar Hypothesis, *Bull. Geol. Soc. Am.*, Vol. 25, 1914. pp. 477-577. Fuller evidence is presented in Climatic Changes, 1922 and in Earth and Sun, 1923.

water important contributory factors. Chamberlin considers the reversed deep-sea circulation, mentioned above, as the probable source of much of the extra warmth present in high latitudes during the mild periods of the past. This reversal he attributes in part to the influence of increased CO_2 in the air with its resultant greater retention of heat, and hence higher oceanic temperatures. Several other agencies have been suspected of being important in producing climatic changes.[44]

9. *The rotation of the earth is such that nearly all parts are lighted and heated by solar radiation for approximately twelve hours and then have darkness for a similar period.* High latitudes, and especially the polar regions (one-twelfth of the globe), are partial exceptions to this rule, as are mid-latitudes near the solstices.[45] However, the oblique angle at which the sun's rays penetrate the atmosphere and strike the surface in high latitudes prevents such excessive heating as would result in low latitudes if the period of heating there were much longer than it is. If the days were 16 hours long in low latitudes, life of the present sort probably would be impossible in the drier regions because protaplasm would be killed by the high temperature. In all latitudes, the coldest normal temperatures occur about sunrise, and the warmest, sometime after mid-day.[46]

10. *Because of the spheroidal shape of the earth and the inclination of the axis, days and nights vary significantly in length in middle and high latitudes.*—They are always the same at the equator and nearly the same to about latitude 20.[47] The disparity increases with the latitude. In July (northern hemisphere) the days average 13.9 hours in

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[44] See Humphreys: The Factors of Climatic Control; *Physics of the Air,* pp. 556-630. Humphreys advocates the efficacy of atmospheric dust. Ekholm, N., (On the variations of the climate of the geological and historical past and their causes, *Quart. Journ. Royal Meteorol. Soc.,* 1901, pp. 1-61) considers variations in the obliquity of the earth's orbit as an important influence supplementing variation in the amount of CO_2. Several writers have considered variations in the distribution and height of the land as the chief and direct cause of the changes of climate. (See Harmer, Influence of winds upon the climate of the Pleistocene, *Quart. Journ. Royal Meteorol. Soc.,* Vol. 27, pp. 303-305, 1901. (Summary), and Clarke, Data of Geochemistry, loc. cit., and Brooks, C. E. P.: Continentality and Temperature, *Quart. Journ. Royal Meteorol. Soc.,* April 1917, and Oct. 1918 (30 pp.), Schuchert, loc. cit., discusses the chief hypotheses advanced before 1914; and Huntington and Visher, Climatic Changes, 1922, all the more important hypotheses.

[45] For the length of day in each latitude and for each day in the year see *Smithsonian Meteorol. Tables,* Washington, 1918.

[46] Meissner reports, *Mo. Weather Rev.,* Vol. 48, p. 39, 1920 that the minimum comes 30 minutes after sunrise from May-September; 15 minutes after during spring and fall; and 10 minutes before in winter.

[47] Salisbury, loc. cit., p. 426.

length at latitude 30; 14.7 hours in length at latitude 40; 16 hours at latitude 50; 18.1 hours at latitude 60; and 21 hours at latitude 65.[48] Long days make summer warmer and long nights make winter colder than they would be if days and nights were always equal. The long summer days of high latitudes permit the growing of crops in extensive areas where those crops could not be grown if the days and nights were equal in length throughout the year (as they are at the equinoxes). Only at the poles is there six months of continuous day or night. All parts of the earth are lighted during one-half of the year.[49]

Effects of Character of Surface.

11. *Land is notably warmer than water in summer and cooler in winter. Land is usually warmer than water by day except in winter in the higher latitudes.*—Water becomes warm less quickly than land and retains heat longer.[50] The ocean thus is a great reservoir of heat in autumn and early winter.[51] In spring and summer it takes up heat from the air which it returns in autumn and winter. The ocean therefore notably affects the temperature of adjacent lands towards which the winds blow. Seas and large lakes act similarly until frozen over.[52] For example, the North Sea often raises the temperature of cold winds blowing from the continent to England as much as 18° F. (10° C.). Lake Ontario and the other Great Lakes likewise often warm cold winds several degrees centigrade.[53] Other effects of unequal heating of land

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[48] Abbe, C., Relations between Climates and Crops, pp. 102-103, *Weather Bur. Bull.*, #36, 1905, for latitudes to 40°. For all latitudes see *Smithsonian Meteorol. Tables*, 1918, pp. 203-214.

[49] Not exactly; there are fewer long nights than long days, in the northern hemisphere, and the opposite in the southern hemisphere. This is due to the earth's elliptical orbit and its greater velocity of revolution when near the sun than when far away. Furthermore all parts of the earth receive sunlight for slightly more than half of the year because of the reflective effects of the atmosphere. The sun is visible when it is about 1° below the horizon. Hence in a year there are about 2/360 more hours of light than of darkness (Humphreys, W. J.: A Bundle of Meteorol. Paradoxes, *Journ. Wash. Acad. Sci.*, Vol. 10, pp. 168-170, 1921.)

[50] Several reasons why water heats and cools more slowly than land are given in Salisbury, Physiography, pp. 454-455, and in Ward, Climate, pp. 36-37.

[51] Pettersson: Meteorological Aspects of Oceanography, *Mo. Weather Rev.*, Vol. 44, pp. 338-341, 1916; and Brooks, C. E. P., cited in note 44 (Abstracted in *Mo. Weather Rev.*, Vol. 47, pp. 653-654, 1919.

[52] The ice will not be as cold as the air above it when that air is very cold, because of the tempering influence of the relatively warm water beneath the ice. Ice however is a very poor conductor of heat; hence ice-covered water bodies contribute heat to the atmosphere so slowly as to have little influence as a source of heat. See, Birge, E. A. Heat Budgets of American and European Lakes, *Transac. Wis. Acad. of Sci., Arts and Letters*, Vol. 18, pt. 1, 47 pp., 1914.

[53] Hann, loc. cit., pp. 179, 180.

and water are land and sea breezes and monsoon winds. Because the ocean is cooler than the land more than half the time, average temperatures are lower along the coast than inland, except in the higher latitudes. "The heat equator" is north of the rotational equator except near Australia because there is more land in low latitudes in the northern hemisphere than in the southern. The greater extent of arid land north of the equator is of especial significance because arid lands are much warmer than the ocean in low latitudes. It is chiefly for this reason that the northern half of the eastern hemisphere averages 4.5° F. (2.5° C.) warmer than the southern half, and the eastern hemisphere 1.8° F. (1° C.) warmer than the western.[54] In the higher latitudes, the ocean is warmer than the land, especially in winter. For example, in Europe between latitudes 47° and 52°, for each 10° of longitude farther from the west coast there is a decrease of 2.4° F. (1.3° C.) in mean temperature and a decrease of 5.6° F. (3.1° C.) in winter, but an increase of 1.3° F. (0.7° C.) in summer.[55]

12. *Snow or ice-covered areas are notably colder than similar areas not so covered except those immediately to leeward,* chiefly because air temperatures much above the freezing point will not occur where snow or ice is widespread. After a temperature of 32° F. (0° C.) has been attained, additional heat received by the surface air usually melts the ice, and becomes latent energy instead of raising air temperatures. Furthermore, the reflection from snow or ice lessens the effectiveness of solar radiation greatly, 40 per cent or even as much as 70 per cent, according to Abbot. A third factor reducing the temperature of snow-covered areas is the evaporation from the snow. Likewise the snow mantle is a good non-conductor and also a poor absorber of heat, and therefore interferes with the warming of the air by heat in the soil. These influences, together with the general dryness of the air in clear weather, often lead to low nocturnal temperatures over snowfields in clear weather.

13. *The vegetal cover affects temperature conditions.*—In forests the air is cooler by day and warmer by night, on the average, than in grasslands, and in other places possessing scanty vegetation. Vegetation absorbs much radiation and reflects some also. Likewise it interferes bodily with the escape of heat from below, which effect is especially prominent at night. Another important way in which vegetation modifies temperatures is in promoting evaporation, a cooling process. It is largely because of the greater evaporating surface which the leaves afford that the temperatures in dense equatorial forests average less

[54] Hann, loc. cit., p. 202.

[55] Ibid, p. 138.

than those at coastal stations.[56] Additional effects of vegetation on temperatures are given under other laws.*

14. *Diurnal and seasonal lag usually increases with latitude, at least in middle latitudes, and decreases with increased aridity.*—Lag is due to the fact that heating is delayed by the presence of ice, cold water, frozen or chilled soil and rock and that cooling is delayed by stored-up heat in water, rock, soil and water-vapor. There is less lag for atmospheric temperatures in arid regions than in humid regions because: (1) There are fewer clouds and less other atmospheric moisture to interfere with radiation; (2) there is little water vapor available for evaporation or freezing; (3) there is a greater exchange of heat by conduction between the atmosphere and the land because the scanty vegetal cover is less effective than the denser vegetation of more humid lands in maintaining a layer of stagnant air between the land and the atmosphere. Another cause of more effective conduction in arid regions is the greater exposure of firm rock there than in humid regions. Rock is a much better conductor than soil.[57] Air over the water reaches its maximum temperature sooner after the time of maximum heating than air over land (about 1 P. M., instead of about 2 P. M.).[58] This is largely because, (1) water heats and cools so slowly that it has only a small diurnal range and hence little positive effect on the diurnal temperature of the air. Thus over the water air temperatures cease to rise almost as soon as insolation decreases. The temperature of the surface of the land is usually higher than that of the air for some time after noon, so that radiation and conduction from it continue to raise the temperature of the air. (2) Since water is a better reflector than land, the decrease in the angle of incidence after noon soon means a much greater reflection from water than from land with a correspondingly greater decrease in effective insolation per unit area on the water. (3) Increased evaporation with higher temperatures also tends to prevent a further rise in water temperatures.[59] In the intermediate zones the amount of seasonal lag averages about a month, but increases with

[56] Ibid, p. 138.

* See Laws 14, 17, 19 and 23.

[57] Patten, H. E., Heat transference in Soils, *U. S. Bur. of Soils, Bull.* 259, p. 49, 1909.

[58] Hann. loc. cit., p. 13.

[59] Only a fraction of the heat entering open water raises its temperature; the rest causes evaporation. The fraction used for evaporation rises rapidly with increased temperature of the water and is very high in tropical seas. (Hann, loc. cit., p. 131). In northern United States and northern Europe, however, according to Birge, E. A., *Trans. Wisc. Acad. Sci.*, Vol 18, 1914, more of the heat is used to raise the temperature than to evaporate the water.

latitude chiefly because of the corresponding increase in the amount of surface water, snow, and ice.

The lag is greater in water than in air and is still greater at moderate depths in the soil. Unless shallow, water is commonly warmest an hour or two before sundown, and two or even three months after the summer solstice. It is coldest an hour or two after sunrise, and two or three months after the winter solstice. The vertical circulation, and hence the amount of lag, is affected, however, by the salinity where average water temperatures are near 39° F. (4° C.), as fresh water is densest at 39° F. (4° C.), while oceanic salt water is densest at 28° F. (2° C.). Depth and heating being equal, the lag is greater in fresh than in saline water. The lag in soil varies with depth. At the greatest depth commonly reached by the diurnal change of temperature (about two to three feet, depending on the kind of soil and on the extent of the atmospheric diurnal range), the highest temperature is at night and the lowest by day. The seasonal change is normally inappreciable below 35 to 70 feet (11-22 meters), even in regions of great seasonal range, and is much less than 35 feet in the tropics with their small seasonal range of temperature, and in polar regions with their frozen subsoil.[60] Near the bottom of the zone of seasonal change in temperature in the soil wherever that zone is deep, the maxima usually occur about five months later than they do in the air above.

RANGE IN TEMPERATURE.—*Diurnal Range.*

15. *Diurnal range in temperature is greatest, other things being equal, where and when day and night are of equal length. Hence it normally decreases with increase in latitude, except near the equinoxes, when the reverse is true.*—When nights are much shorter than days nocturnal cooling does not last long enough to reduce the temperature so much as when nights are longer. On the other hand short days seldom become warm enough to produce a marked diurnal range. Near the equinoxes, diurnal range tends to increase with latitude, because the decrease in absolute humidity characteristic of increase in latitude allows more rapid heating and cooling in higher latitudes than in lower latitudes. These normal relationships between daily range and latitude are interfered with in the cyclonic storm belts because intense storms occasionally increase daily range notably. Furthermore, three influences locally interfere with the normal seasonal occurrence of the greatest ranges. Instead of coming at the equinoxes, some places have a greater average range in winter, because of augmented storminess at that season, with resulting occasional sharp temperature changes within 24 hours. Places with dry seasons often have the greatest ranges in the

[60] Bowman, I., Forest Physiography, p. 60, 1911.

dry months since aridity favors a wide range. (See Law 17, beyond.) Finally, seasonal changes in wind direction give some places near coasts a smaller range at one season than at another. (See following law.)

16. *Diurnal range in temperature increases with decrease in the influence of the ocean or of lakes* as water tends to prevent the temperature from rising notably by day and from falling low at night. The average diurnal range in the surface waters of the ocean varies from 2-5° F. (1.1°-2.8° C.).[61] On the other hand, the average diurnal range over the land is more than 12° F. (7° C.) and the temperature of the surface soil or rock is often several degrees colder or warmer than that of the air a few feet above. The air over water is kept warm at night in three ways: (1) The large amount of heat given up by the water, due to its high specific heat. (2) The vertical movements, by which warmer and hence less dense water from below replaces the partially cooled surface water. (3) The abundance of atmospheric moisture and the frequent cloudiness above water bodies checks the loss of heat by radiation at night.

17. *Diurnal range in temperature increases with aridity, on the average.*—A large range is less common in humid than in arid regions because humid regions have more atmospheric moisture, greater cloudiness, more evaporation, more condensation, more dense vegetation and more moist soil. In humid regions atmospheric moisture greatly hinders surface absorption and loss of surface heat by radiation, and in addition clouds often check insolation by day and loss of heat by radiation at night. Furthermore, in moist areas much heat is used during the day to evaporate water. This latent energy is returned to the air as heat when condensation takes place, as when dew is formed at night. The greatly increased evaporation at higher temperatures is an important factor in preventing temperatures from rising much above 100° F. (38° C.) in moist regions. Twice as much moisture can be contained in a given space at 108° F. (42° C.) as at 90° F. (32° C.). The formation of fog and clouds at night often prevents frost by liberating heat in condensation as well as by checking the loss of heat by radiation. The influence of cloudiness on nocturnal cooling is well illustrated by data reported by Hellman.[62] On a clear night in Germany, the average temperature one-half meter above the surface is 6.7° F. (3.7° C.) higher than at the surface, while with an overcast sky there is no difference. Furthermore, when the sky is one-tenth overcast the

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[61] Ward, R. De C., Climate, p. 37; quoting from Challenger Report. For an excellent summary see: Buchan, Alex., Meteorological Results of Challenger Expedition, *Proceed. Royal Geogr. Soc.*, Vol. 13, pp. 137-156, 1891.

[62] *Mo. Weather Rev.*, Vol. 48, p. 38, 1920.

temperature contrast is one-tenth less than on a clear night. Dew formation with its notable release of latent heat of vaporization is also often significant in preventing low temperatures. Sometimes it prevents frost. Indeed, the lower the relative humidity at 8 P. M., the greater is the expected cooling by morning.[63] The influence of vegetation and soil in affecting conduction has been mentioned. (Law 14.)

Even in deserts certain influences prevent excessively high air temperatures by day: (1) The loss of heat by radiation is rapid because of low humidity and slight cloudiness; (2) the rate of radiation increases rapidly with increases in temperature (varying as the fourth power of the absolute temperature for black bodies—Stefan's Law); (3) conduction of heat into the earth is favored by the abundance of bare rock; (4) the prevalent convectional winds by day carry much heat aloft; (5) the increased dustiness induced by the high winds and whirlwinds checks insolation. These five influences and the shortness of the days, usually prevent the occurrence of temperatures higher than about 120° F. (50° C.). Low temperatures at night are delayed, not prevented, by the dust because most dust in deserts is coarse and low and much of it settles during the prevailingly calm nights. Furthermore the dust radiates heat readily and before morning is colder than the surrounding air, which it then helps to cool by conduction. Whereas the daily range in air temperature in humid areas is often less than 10° F. (5.6° C.) and commonly less than 20° F. (11° C.), in warm deserts it is usually more than 30° F. (16° C.), often more than 50° F. (28° C.), and not rarely 70° F. (39° C.). Indeed dark-colored rocks in the Sahara often experience a diurnal range of nearly 176° F. (80° C.).[64]

18. *Diurnal range in temperature increases with altitude up to the snow-line for places similarly exposed, except on some valley slopes.*—This is because at higher altitudes there is progressively less air, less water vapor, less CO_2 and less dust. Decrease in these latter substances is significant because together they absorb nearly all of the radiant energy absorbed by the air.[65] Air pressure is significant in this connection because molecules of all gases scatter or diffract an important

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[63] Hann, loc. cit., p. 145. For a much fuller discussion of this point see Smith, J. Warren,: Predicting minimum temperatures from Hygrometric Data, *Mo. Weather Rev.*, Supplement, No. 16, 1920.

[64] Hann, loc. cit., p. 147, quoting Walther.

[65] According to Ganot's Physics, (p. 630) CO_2 has 90 times the absorption power of ordinary air, and water vapor has 70 times the absorption power of dry air. For a fuller discussion of this subject, however, see Humphreys, Physics of the Air, pp. 88, 606-608, 1920.

fraction of solar radiation.[66] Above an elevation of two miles (3 km.) the scattering is chiefly molecular. Below that level, dust is important.[67] Scattering interferes with the passage of radiant energy. Hence, because of lessened atmospheric absorption and lessened diffraction, a larger fraction of solar radiation is available at high than at low altitudes for daytime warming of favorably exposed surfaces. For the same reasons the loss of heat by radiation is very rapid at night, and by day from places in the shade. Certain conditions at high altitudes are adverse to large diurnal range, but are not sufficient to prevent a general increase in range with increase in altitude.[68] For example: (1) In spite of the frequently large ranges of temperature of favorably exposed rocks, air temperatures are slightly affected because the air normally passes too rapidly, because of the strong winds, to be affected appreciably by conduction or radiation from or to the small rock surface. (2) The "down drainage" of cool, heavy air at night often results in valleys being cooler than adjacent heights of moderate elevation. The cool air moves outward from the hillside and slightly downward as the colder air lower in the valley settles. It is replaced by somewhat warmer air from greater distances from the cold surface. The accumulation of cold air in valley bottoms results in the zone of highest temperatures being found some distance up on the valley sides, though below the normally colder hilltops and peaks. Such warmer zones are sometimes "frost free" in the fruit-growing season.[69] In free-air the diurnal range decreases with height. There is often a difference of 5° F. (3° C.) between the surface temperature and that of the air five feet (1½ meters) above, and sometimes in dry areas there is a difference of 14° F. (8° C.).[70] This is because air is a much poorer radiator than soil or rock.

19. *Diurnal range in temperature increases with decrease in vegetation:* (1) Bare soil or rock, especially if dark-colored, as it commonly is, absorbs more radiation than do most plant-covered areas. There is much reflection from leaves, many of which are light-colored and most of which are somewhat shiny. (2) There is more evaporation

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[66] Abbot, Fowle and Aldrich, *Proceedings Nat'l Acad. of Sci.*, June 15, 1915, pp. 331-33, and, more fully, in *Annals of the Astrophysical Observatory, Smithsonian Institution*, Vol. 3.

[67] Angstrom, A., Scattered radiation from the sky, *Mo. Weather Rev.*, Vol. 47, p. 797, 1919.

[68] Hann, loc. cit., p. 238.

[69] See Cox, H. J., Thermal belts in the North Carolina Mountain Region, and their Relation to Fruit Growing, *Annals Assoc. Am. Geographers*, Vol. 10, pp. 57-68, 1920.

[70] Hann, loc. cit., p. 42.

from vegetation than from the average soil or rock-covered area. (3) A small part of the energy absorbed by plants is used in photosynthesis becoming latent in carbohydrates. (4) Vegetation hinders the escape of heat from the soil, and from the entrapped air, especially at night and thus delays cooling sufficiently to prevent minima so low as those reached in bare areas, or in the air above the vegetation. The escape of heat is reduced by the absorption of radiation from the soil by the subaerial parts of the plants and the subsequent return of part of this energy to the earth by downward radiation. The greater humidity of the air near plants as compared with more remote air acts in the same way. Furthermore, vegetation interferes bodily with convection. The way in which vegetation decreases the loss of heat at night by conduction has been mentioned in Law 13. Because of these influences the diurnal range in forests averages several degrees less than in adjacent fields.[71] However, when deciduous trees leaf-out in spring frost is perhaps sometimes induced by the sudden increase in evaporation.[72]

20. *Diurnal range in temperature differs with differences of slope.*—A slope inclined toward the noonday sun is heated more during the day than one not so inclined but both cool to nearly the same temperature by morning. Steep slopes usually have less range than gentle slopes equally well situated in respect to insolation, because on steep slopes warm air is more quickly removed by upward convection during the day, and cold air by drainage downward at night and thus the temperature of the surface on steep slopes is more nearly equal that of the free-air, than is the case with gentle slopes.

Interdiurnal Variability.

21. *Interdiurnal temperature variability increases with latitude up to subpolar latitudes if other conditions are equal.*—In tropical latitudes nearly all days have similar temperatures, as do the nights. In high latitudes there is great contrast among both the days and the nights. This variation is the result of: (1) Increased disparity in the length of day and night with increase in latitude; (2) the fact that in middle and high latitudes, wind direction is much more significant in changing local temperatures than in low latitudes, where almost all winds are warm; (3) storms also increase the variability, and storms apparently increase in frequency and intensity, on the average, with latitude to subpolar latitudes. One of the ways in which storms cause this variability is in producing interdiurnal changes in cloudiness.

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[71] Fernow, Abbe, and others, Forest Influences, *Bull.* 7, *Forest Service, U. S. Dept. of Agri.*, 197 pp., 1893.

[72] Mayer, A. G., Radiation and absorption of heat by leaves, *Am. Jour. Sci.*, 3rd series, Vol. 145, pp. 340-346, 1893.

Seasonal Range. 22. *Annual or seasonal range in temperature increases with latitude to the region of persistent snow and ice* because of the increased significance of the changes in the angle of insolation, and the increased contrast in length of day and night. Long days in summer tend to produce high maxima. Long nights in winter tend to produce low minima. There is a rapid lowering of minima with increase in latitude and a less rapid lowering of maxima. As minus departures from the normal temperature are usually greater, and often twice as great as the plus departures, low minima are more important than high maxima in producing great seasonal range. The regions of extreme range are therefore on the continents in high latitudes where the winters are long but where snow does not persist throughout the year and thus prevent high maxima; *i. e.,* in the interiors of Northern Asia (range 170° F.; 94° C.), and in northern North America (range 160° F.; 89° C.). The extreme range in the Sahara is only 90° F. (50° C.). Near the equator the average annual range, based on monthly means is 5° F. (3° C.) or less; for latitude 20, about 13° F. (7° C.); for latitude 30, about 18° F. (10° C.); for latitude 40, about 26° F. (13° C.); and for latitude 50, about 46° F. (25° C.).[73] The average annual range for the land based on extreme maxima and minima is about 40° F. (22° C.) near the equator, about 80° F. (44° C.), in latitude 30, and about 120° F. (67° C.) in latitude 60.[74]

23. *Annual or seasonal range in temperature becomes greater with decreases in the influence of the oceans, in the amount of moisture present in the air, soil, or on the surface, and with reduction in vegetation,* because conditions favorable for high temperatures by day, favor high summer averages and maxima, and conditions favorable for low temperatures at night favor low winter averages and minima. (See Diurnal range, Laws 15-20 for reasons.) Marine climates have little range compared with continental climates. The average annual range in marine climates is 15° F. (8.3° C.) for latitude 35 N., and 14.8° F. (8.2° C.) for latitude 60. For continental climates, latitude 40 has a range of 52° F. (29.5° C.), and latitude 60 a range of 88° F. (48.6° C.). The mean for these different latitudes gives the range for marine climates as 14.8° F. (8.2° C.), while that of the continental climates is 70° F. (39° C.), or nearly five times as great.[75] The contrast between continental and marine climates is on the average less in latitudes 0-40 than in higher latitudes, because annual range decreases with latitude. Nevertheless it remains notable.

[73] Supan, quoted by Hann, loc. cit., p. 135.

[74] From Bartholomew's Charts, loc. cit.

[75] Hann, loc. cit., p. 142.

American examples of seasonal range follow:[76] Western Oregon has a normal seasonal range of only about 18° F. (10° C.), while South Dakota has a range of 60° F. (33° C.). The extreme ranges for these places are about 85° F. (46° C.) and 165° F. (91° C.), respectively. Because of the increased dominance of continental conditions, seasonal range commonly increases toward the east on land areas in the westerly wind belt, although the eastward increase in humidity, as in the eastern United States, tends to counteract this influence. Examples of the increase in range toward the east are: Southwestern Arizona has a monthly range of 30° F. (17° C.) and Northwestern Georgia, one of 35° F. (19° C.) the extreme ranges at Yuma, Ariz., and Columbus, Ga., are 100° F. (55° C.) and 112° F. (62° C.), respectively. Nevada has a monthly range of almost 5° F. (2.8° C.) less than Illinois or Pennsylvania. Some stations in southern Minnesota have less range than some in northern New York, in spite of the tempering influence of the Great Lakes. An illustration of the influence of vegetation on annual range is the fact that in Austria the average temperature in the forest is 2° F. (1° C.) lower in summer than outside of forests, while in winter the difference is negligible.[77]

24. *Annual or seasonal range increases with altitude up to the snowline,* because at high altitudes heating of slopes inclined toward the sun is less interfered with by dense atmosphere, dust and moisture, than at lower altitudes, while cooling at night and in the winter is facilitated by the normally strong winds and by the reduced atmospheric interference with the escape of heat. Lofty plateaus have a greater range than lowlands in similar latitudes. For example, stations with an elevation of 5,000 feet (1500 m.) in eastern Oregon have a seasonal range of about 10° F. (5.5° C.) above that in eastern Washington at an elevation of less than 1,000 feet (300 m.), but otherwise similar.[78] Above the snowline, however, the seasonal range is not so great because summer temperatures are prevented from rising nearly so high as they do below the snowline.

25. *Seasonal range in temperature is affected by topography.*—Slopes inclined sharply toward the midday sun are warmer in summer than those not so inclined, while in winter they may be equally cold, and thus have the greater range. Favorably situated valleys are usually warmer than nearly level stretches (although they may sometimes

[76] Charts of Normal Temperatures and Extreme Temperatures for the United States, *U. S. Weather Bureau,* 1912.

[77] Hann, loc. cit., p. 31.

[78] Charts of Normal Temperatures and Extreme Temperatures for the United States, *U. S. Weather Bureau,* 1912.

be notably colder at night—see No. 18, above). Such valleys are normally warmer because: (1) Foehn breezes or winds often prevail; (2) the more effective heating of those portions which receive vertical insolation may more than compensate for the less effective heating of slopes not so favorably situated for heating as are level tracts. (3) Radiation from the sides of warm valleys interferes with loss of heat by radiation from the valley bottom, or in case of a narrow valley, from the other side,[79] probably because of the larger radiating surface in proportion to the volume of air within the valley receiving the radiated heat. Some favorably located areas have their temperatures notably affected by reflection from water bodies, snow, or light soils. The maxima are often several degrees higher than those at nearby points.[80] The minima are usually as low, because diurnal and extreme minima normally occur at night. Furthermore, by day the sun shines at a lower angle in winter and the reflection thus affects a different area.

Variability from Year to Year. 26. *Variability or irregularity in temperature conditions from year to year and for corresponding months tends to increase with latitude nearly to the region of persistent snow, with aridity, with storminess, and with decrease in the influence of the ocean.*—Equatorial days and seasons resemble one another strikingly in so far as temperature is concerned, while in mid-latitudes, no year or season is "normal." Temperatures are distinctly more uniform in humid areas than in arid regions otherwise similar. Variability increases with latitude for a number of reasons: (1) Slight fluctuations in the effectiveness of insolation and radiation are more appreciable where little insolation is received than where much is received. Differences in cloudiness and precipitation produce fluctuations of this sort in high latitudes. (2) Changes from year to year in direction and velocity of the wind produce greater changes in temperature in high than in low latitudes, where nearly all winds are warm. Differences in storm paths and storm intensity produce many such changes in the average wind direction for the year. (3) In so far as storminess increases with latitude it helps to explain this law. The greater variability of weather in winter than in summer is largely due to greater storminess in winter. The stabilizing influence of snow and ice makes polar conditions somewhat more uniform in some respects than those in subpolar regions. Variability increases with distance from the ocean because of the lessening influence of that great stabilizer of temperature conditions. Variability increases with aridity because irregularity in the amount of clouds and surface water increases in

[79] Davis, loc. cit., pp. 31, 157.

[80] Hann, loc. cit., p. 40.

that direction. An exception to this latter rule occurs in extremely arid regions on the lee side of mountains where conditions are fairly uniform. Illustrations of this general law are Hann's statements that a 40-year record would be required in central Europe to obtain as accurate an average annual temperature as a two-year record from Java would give. In Siberia records for more than 100 years would need to be averaged to obtain a monthly average as accurate as a five-year record would give in Java. Eight hundred Siberian winters would give an average no more nearly correct than would 100 summers.[81]

[81] Hann, loc. cit., pp. 9, 10.

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SOILS OF THE GREAT PLAINS

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CONTENTS.

INTRODUCTION.—The Great Plains, as defined in this paper, is a region in which certain soil characteristics prevail. No attempt whatever is made, in this definition of the region, to conform to any of the other definitions that have been proposed or used. The paper is written for the purpose of describing the soils of the region and for that reason soil character will be given the predominant attention

not only in the details of descriptions but in the definition and delimitation of the region.

THE GENERAL FEATURES OF THE SOIL.—The Great Plains, thus defined include that part of the United States, lying east of the Rocky Mountains, in which the soils are characterized, at maturity of development by (1) the presence, on some horizon of the soil section or profile, of a zone of alkaline salt accumulation, usually, not exclusively, lime carbonate and (2) a relatively dark colored surface soil. The color varies, from place to place, in degree of darkness but throughout the region it is darker than the mature soil in any other part of the country in which the zone of salt accumulation is present in the soil.

These are the two characteristics that are universally present in the soils of the Great Plains. Neither can be accepted as an exclusive characteristic taken alone since the dark color of the soils, even of mature soils, is present in regions far beyond the limits of the Great Plains where the salt zone is not present and, on the other hand, the salt zone is present in large sections outside the area of the Great Plains but the dark color of the surface soil is lacking.

The dark color of the soil extends several hundred miles east of the eastern boundary of the Great Plains while the presence of the salt zone extends far west of the region in which the soils are dark in color. The two characteristics therefore are not coincident in their distribution, the one extending eastward beyond the area in which both are present and the other extending westward beyond the same area. The region in which the two overlap is designated as the Great Plains.

The position of the Rocky Mountains, along the western boundary seems to be accidental, it being apparent that the western boundary would lie about where it is if the Rocky Mountains were not in existence. This is suggested by the fact that the mountains do not everywhere form the boundary and where absent there is no important deviation of the line from the general course taken by it in places where they are present.

THE BOUNDARIES OF THE GREAT PLAINS.—*The Eastern Boundary.*—Since a dark surface soil is characteristic not only of the soils of the Great Plains, but of an extensive region east of the Great Plains, it is evident that the eastern boundary of the region must be determined on the basis of the other characteristic of the Great Plains soils,—the zone of carbonate* accumulation. Since the Great Plains region as defined, does not extend east of the area in which the zone of carbonate

* Since the zone of salt accumulation is so predominantly a zone of carbonate accumulation, the latter expression will be used hereafter in this paper and the reader should understand also that it means in practically all cases a zone of lime carbonate accumulation.

accumulation is present it is evident that the eastern boundary is also the boundary of the zone of carbonate accumulation.

Since nature rarely establishes sharp boundaries, and since man must usually do so, we define the eastern boundary of the Great Plains as the line along which the zone of carbonate accumulation, universally† present throughout the Great Plains, disappears entirely or becomes so faintly developed that it cannot be identified by ordinary field observation. The zone may be very faintly developed in favorable localities east of the line here described.

Beginning at the northern boundary of the United States, the eastern boundary of the Great Plains enters the country from Canada a few miles east of the northwestern corner of Minnesota, runs thence southward by Alexandria and Big Stone Lake, Minnesota, approximately along the South Dakota-Minnesota boundary to the southern part of the State, cuts off the southeastern corner of South Dakota, passes within a few miles of Norfolk, Nebraska and about 20 miles west of Lincoln, entering Kansas a few miles east of Mankato. It continues thence southward running some 20 miles east of Pratt, Kansas, passing in the vicinity of El Reno, Oklahoma, Henrietta and Olney, Texas to the vicinity of Baird, Texas. It crosses Coleman County, Texas in an irregular line running in places eastward into Brown County, runs east of Brady, crosses the Edwards Plateau not far from Mason and Fredericksburg, thence through San Antonio and Beeville to Corpus Christi. (Fig 1)

The Western Boundary.—It has been stated above that the Rocky Mountains bound the Great Plains on the West. This is in general true, but, as has already been stated, they seem to be more or less accidentally situated along the western boundary since this line would be, in part at least, where it is if the mountains did not exist. The western boundary where the mountains do not fix it, must be established on the basis of soil color, since the other soil characteristic of the Great Plains, the presence of a zone of carbonate accumulation, extends westward far beyond their western boundary. The western boundary therefore lies along that line or zone which divides the dark colored soils of the Great Plains from the light colored soils of the region west of the Great Plains, leaving the mountains out of consideration.

† To say that the salt zone is *universally* present in the soils of the Great Plains is not strictly correct nor would it be strictly correct to state that all animals of the Jersey cattle breed have horns. They do not have horns until they have attained a certain stage in their development. In the same way the *undeveloped* or *immature* or *young* soils of the Great Plains do not have a zone or horizon of lime carbonate anywhere in the soil section. It is present only in those soils that have attained a stage in their development that would correspond in organic beings to the stage described as mature. To be strictly accurate therefore the phrase should run somewhat as follows: Universally present *in the mature soil* throughout the Great Plains.

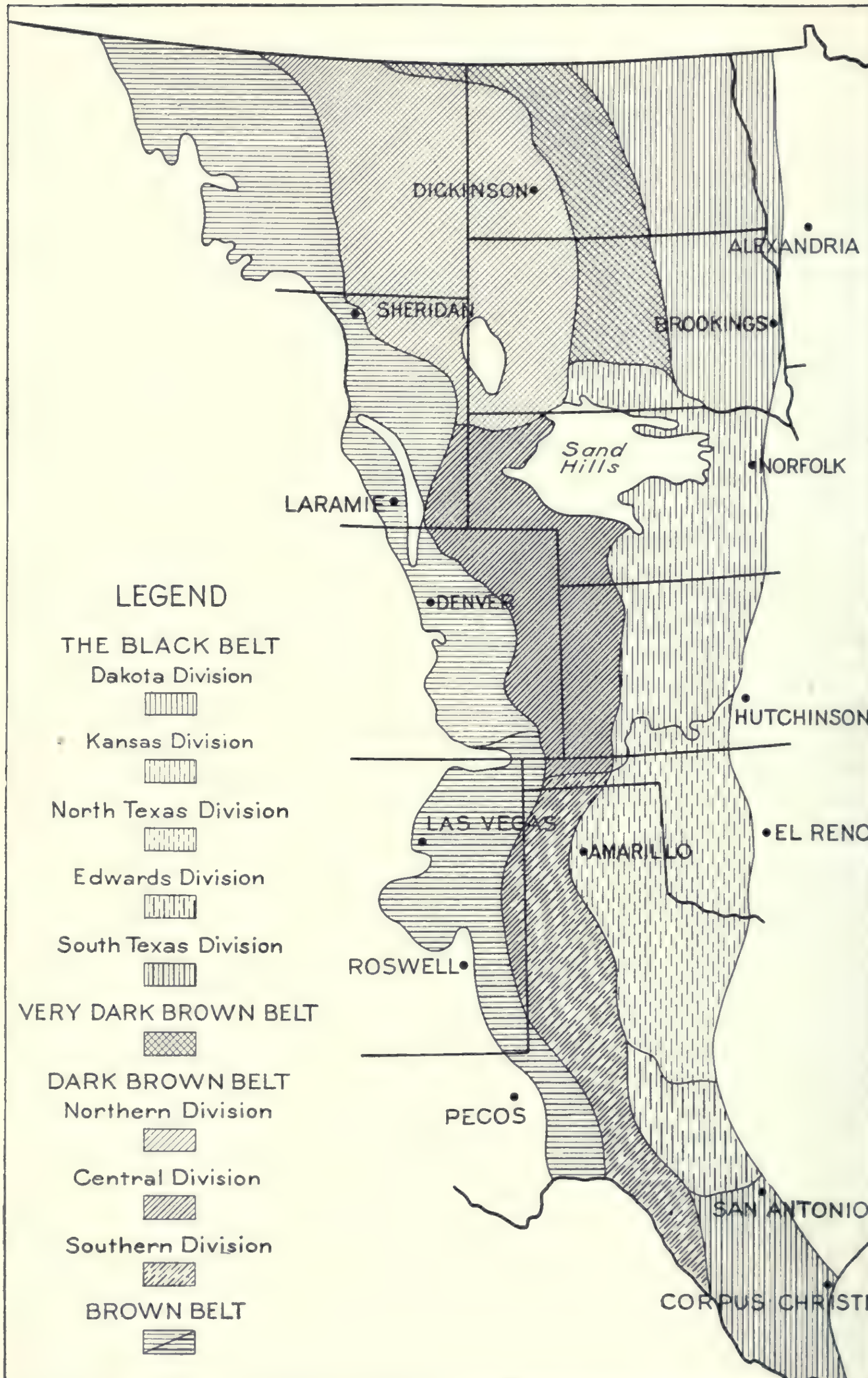


Fig. 1. Soil Map of the Great Plains

In the northern section the eastern foot of the mountains forms the western boundary of the Great Plains from the Canadian boundary southward by Helena, Whitehall, Livingston and Red Lodge, Montana, Sheridan and Buffalo, Wyoming. From the south end of the Big Horns to the mountains southeast of Rawlins, Wyoming. the boundary does not coincide with the mountain base. South of that point it follows the Rocky Mountain front by Denver, Colorado Springs and Trinidad, Colorado, Raton and Las Vegas, New Mexico. Thence to the Rio Grande it does not follow a mountain chain. The mountain range, south of Las Vegas, New Mexico, is broken up into isolated mountains.

Where the boundary would be, along the northern line of the United States, if the mountain range were not present, cannot be stated definitely. It is true however, that west of the mountains, a region of importance, both in size and value from the point of view of productive capacity, is essentially identical in soil character, and in many other features as well, with the Great Plains. This is the well known Palouse region in eastern Washington and eastern Oregon. While this is however a region identical with the Great Plains in soil character, yet it cannot be considered as a part of that region cut off from the main body by the mountains. This is evident from the details of its features. It is not a continuation of the Great Plains but another Great Plains in miniature and will have to be considered as an independent region due to local conditions. If the mountains were not present it would not exist, but its place would in all probability be occupied by gray desert soils.

The western boundary of the Great Plains proper, were the mountains not present, would lie, somewhere between the eastern and western mountain fronts, probably not far from the eastern.

In the stretch between the south end of the Big Horn range and the north end of the Colorado ranges, southeast of Rawlins, the western boundary of the Great Plains runs southward without significant divergence from its course along the Big Horns. The Laramie range is a feature lying within the Great Plains like the Black Hills of South Dakota, the several ranges surrounding the Judith Basin and other isolated mountains in Montana. West of Caspar and Sussex, Wyoming, the soils become too light in color in a short distance for this section to be included in the Great Plains.

South of Las Vegas the line as placed on the map swings westward and southward but swings back across the Pecos a short distance north of Roswell, New Mexico, turning south along the east side of the stream reaching the Rio Grande west of Sanderson, Texas.

There are a number of areas west of the Great Plains that have Great Plains characteristics. They are all isolated, none of them being continuous with the Great Plains, and all are due to local conditions. An important area of this character covers the highlands of New Mexico from a few miles west of Socorro to, and beyond, the Arizona boundary. It is a narrow belt, just north of the forested area which lies on the watershed separating the southward drainage, mainly to the Gila, from the northward drainage, mainly that of the Little Colorado, and the desert country to the north. Other areas, with more or less definite Great Plains characteristics occur throughout the mountain region of the west.

The western boundary of the Great Plains therefore, for a considerable part of its stretch, is accidental, formed by what, from the soil point of view, is the accident of mountain building. That this is accidental and that the region would have had a western boundary that could have been defined in terms of soil characteristics is shown by the fact that such a western boundary is actually present where the mountains do not exist.

THE SOIL BELTS.—The soils of the Great Plains are uniform to the extent, as has been pointed out already, that they are dark in color and are underlaid by a zone of lime carbonate accumulation Fig. 1. They differ however in the degree of darkness of the soil color from place to place and in the depth as well as in other minor characteristics of the carbonated zone. The change in color and the change in depth to the zone of carbonate accumulation are complementary; as the color decreases the carbonate zone rises and *vice versa*.

Since the soil color is a surface feature, and more easily and directly open to observation than the other, it is more convenient to use the change in color as a basis for the subdivision of the soils of the region into soil subgroups, these being further subdivided into areas. There is a progressive decrease westward in the darkness of the soil color. This is true regardless of the latitude on which the examination is made. The color changes somewhat from north to south also as will be shown below, but in all latitudes the color along the eastern boundary has a maximum degree of darkness for the particular latitude selected with a minimum degree along the western boundary.

The region as a whole may be readily divided into three north-south belts of soil, on the basis of the darkness of soil color, which we may designate as (1) the Black Belt, (2) the Dark Brown Belt, and (3) the Brown Belt, and for the northern end of the region it is convenient to insert a Very Dark Brown Belt between (1) and (2). The general distribution of these belts, so far as existing knowledge will permit its mapping, is shown on the map (Fig. 1) and needs no description. It is

shown in a somewhat diagrammatic way, as though the belts were continuous and unbroken from one end to the other. This is done in order to give them clear expression. Certain minor modifications are details, some of which will be located and described later in the paper.

The Black Belt.—The Black Belt seems to be the equivalent of the Black Earth or Chernozem of the Steppes in European and Asiatic Russia. The soil is black, or is the darkest of the Great Plains soils, and the carbonate zone lies, in the United States, at a depth ranging from 2 to 5 or 6 feet. Not only does the surface soil have a maximum of darkness but the thickness of the dark colored horizon is a maximum, ranging in the normal soil from about 8 or 10 inches to about two feet. While these general characteristics prevail throughout the whole belt, there is considerable variation in them in detail, and certain minor characteristics present themselves in the different parts of the belt.

On the basis of soil characteristics the Black Belt may be subdivided into five areas or divisions which may be designated as (a) The Dakota Division (b) The Kansas Division (c) The North Texas Division (d) The Edwards Division and (e) The South Texas Division.

The Dakota Division.—The Dakota Division occupies the northern end of the belt. Its area and extent are shown on the map (Fig. 1). The soils in this division are blacker and the dark colored horizon is in general thicker than in the other divisions. The carbonate zone, taken as a whole is shallower than in the other areas, except possibly in the Edwards Division.

Very little attention has been given to the details of the soil profile, especially as regards the structure of the soil. In the northeastern part of the area the soils, being developed from lake deposits, are rather heavy in texture over large areas. Around the borders of the section of heavy soils, the basin of the extinct Lake Agassiz, however, there are considerable areas of sandy deposits which have developed into sandy soils. On the rolling uplands of the rest of the state, underlaid by glacial drift, the predominant textures are loams and very fine sandy loams. In the James River valley there are large areas of smooth lands underlaid by gravel beds within a few feet of the surface, though the soils above the gravels are usually loams. Sand areas lie irregularly distributed over the whole region but do not form any considerable part of it.

The shallow depth at which the carbonate zone has formed is possibly due mainly to the highly calcareous nature of the parent glacial drift from which the soils have developed. It seems that a high percentage of lime carbonate in the parent material causes the formation, at

an early stage in soil development, of a carbonate zone at a shallow depth; this is later driven downward as leaching progresses until equilibrium has become established in accordance with the rainfall,—this final position being wholly independent of the character of the parent rock. It seems probable that the reason the soil in this division is darker than in the others is due, in part at least, to the same highly calcareous parent rock. Soils developed from calcareous parent rocks, at a certain early mature or still earlier stage of development are universally darker in color than the same soils in a later stage of the cycle. It seems probable therefore that these soils are now in that early stage of development in which the calcareous parent rock expresses itself effectively in the color of the soil. Such soils are well known elsewhere. The Black Soils in the Black Belt of Alabama and Mississippi are of this character; so also are the "Black Waxy" soils of Texas. These black soils of Texas, Alabama and Mississippi lie in a region in which the well matured soil is light in color and when these black soils finally become mature they will, presumably, assume the characteristics of the mature soils of the region in which they lie. The North Dakota soils however lie in a region in which the normal or mature soils are dark in color and when in their development they assume the normal color of the soils of the region they will not become light in color. Indeed they will not be essentially different in color from what they now are, since the normal soils of the region are black. They will lose their *local* black color and assume a *regional* black color.

Soils that are black due to the persistence of the influence of a calcareous parent rock are known as *Rendzinas,* a term applied by Polish peasants to the limestone soils of Poland. The soils of the Dakota Division seem therefore to be half Rendzinas and half Chernozorus, but as they develop they will gradually lose their Rendzinas characteristics and assume more and more the characteristics of true Chernozorus. Since the soils of both groups are black the change will not be a noticeable one. The main change that will take place will be the gradual downward movement of the carbonate zone, finally halting at a depth of from 3 to 5 feet.

In parts of this region, in Beadle County, South Dakota especially, a soil, with a profile varying markedly from the typical profile of the region, extends over a considerable area. The variation is a feature of the subsoil and consists of the presence of a heavy, tough, usually dark colored horizon, varying from six inches to a foot or more in thickness, lying beneath the soil and above the rather heavy but not tough shaly glacial drift. Its presence seems to be due to the presence

of sodium salts in small amounts in the soil water, causing a deflocu-lation of the surface soil, a washing downward of the defloculated clay particles and a refloculation and accumulation of these particles in the subsoil due to a change in composition of the salts. The amount of salts present is not sufficient to cause injury to growing plants but the heavy subsoil is somewhat unfavorable to plants because of its influence on the amount and availability of the subsoil moisture. The total thickness ranges from 10 to 20 inches.

The Kansas Division.—The Kansas Division lies south of the Dakotas, its location and extent being shown on the map (Fig. 1). A typical profile or section of the soil in this area is about as follows:

1. Grayish black to black horizon, showing a horizontal arrangement of particles but not stratification and with no noticeable granulation, the thickness varying from a mere film to about 5 inches. (Not always present.) 2. Black to grayish black, highly granular horizon very little heavier in texture than No. 1, ranging from 8 to 18 inches in total thickness. 3. Dark gray to gray, heavy horizon, somewhat granular at top but losing the granulation in a few inches, with a very marked capacity for breaking into vertical columns of 2 to 3 inches in diameter where exposed in banks. 4. Yellowish brown horizon, often breaking on drying into small vertical columns. This horizon is not always present. It ranges up to 6 inches in total thickness. 5. Gray, loose, friable horizon, highly calcareous. The carbonate zone. 6. The parent geological formation which may range from loose, through glacial drift to the disintegrated material from various sedimentary rocks. (Pl. I. a.) Horizon 3 is sometimes absent especially on the rolling lands and in these cases horizon 4 is likely a foot or more thick.

The carbonate horizon lies at greater depth in the soils of this division than in those of the Dakota division. The soils seem to have become more maturely developed and the carbonate horizon to have reached a stable depth. The heavy horizon (Pl. I. c) is developed on the flat lands throughout the region but is not everywhere equally heavy. It seems to be characteristic of a larger area in Nebraska than in Kansas and seems also to be better developed, other things being equal, in the eastern part of the area than in the western part.

The color of the soil is less black than in the Dakota region and it is also less black than is the Black Earth of Bessarabia and parts of Roumania. It seems to be more like that of the dark colored soils of the Hungarian plain and the better parts of the Plains of Thessaly in Greece. The color is grayish black rather than the dense coal black of the soil in Moldavia, Roumania. The grayish shade seems

to be as characteristic of the soil in the eastern part of the area as in the western, differing seemingly in that respect from the same soils in European Russia.[1]

The Kansas Division is a region with agricultural characteristics as well defined, taken as a whole, as are those of the Dakota Division. The latter is the region of predominant spring wheat, this is the region of predominant winter wheat. The extreme northern portion of the area has a climate a little too severe for a perfectly safe winter wheat agriculture and is a little too far south for spring wheat. Corn assumes an importance equal to wheat but in the greater part of the area winter wheat is not only the predominant, but almost the only crop.

The North Texas Division.—The location and extent of this division, which includes portions of Kansas, Oklahoma and Texas are shown on the map (Fig. 1.) A typical profile in the northern part of the area is about as follows:

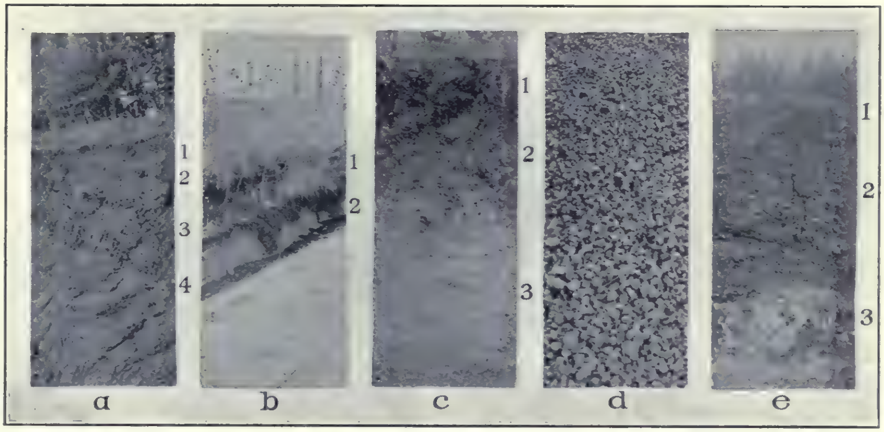
Soil Profile at Stamford, Texas.—(Pl. I, c, d,e).

1. Dark brown loam with reddish shade........	0 to 10	inches
2. Reddish brown clay loam, granular...........	10 to 18	inches
3. Pinkish highly calcareous clay loose..........	18+	inches

These profiles differ from that of the Kansas Division in several respects: The soil as a whole is not so dark in color. The highly granular subsurface horizon is not so well developed as in the Kansas Division; the heavy, cloddy horizon with columnar breakage,—so well marked as No. 3 in the Kansas profile is less well developed here; a reddish brown color which was not present in the Kansas section becomes well defined in the subsurface; the reddish or pinkish color persists into the carbonate horizon in the North Texas Division; and the carbonate horizon becomes much more highly calcareous, with sharper upper boundary, than in the Kansas Division. The dark color of the surface soil and the carbonate zone are the two features that are common to all the divisions described so far. The granular horizon is present in the North Texas area; it is merely somewhat less pronounced in its development than further north. The change from the characteristics of the Kansas area to those of the North Texas area takes place gradually.

Certain characteristics of soil development. It becomes necessary at this point to turn aside to discuss briefly a feature of soil development under certain conditions of environment which has a pronounced influence on the details of soil character and distribution.

[1] D. K. Glinka, Die Typen der Badenbilding, Berlin 1914, Page 116



a. Soil profile near Belleville, Kansas. Horizon 1, is the granular horizon; 2, the heavy cloddy imperfectly columnar horizon; 3, the brown finely columnar horizon; 4, the carbonate horizon. Kansas Division of the Black Belt.

b. Soil profile near LaCrosse, Kansas. Shows only the dark colored horizon and the carbonate zone. Kansas Division of the Black Belt.

c. Soil profile at Westover Texas, representing the North Texas Division of the Black Belt in a locality where the red color is not developed. Horizon 1 is the granular horizon, 2 the heavier, cloddy horizon and 3, the carbonate horizon.

d. Shows the granular structure of horizon 1 in c

e. Soil profile at Amarillo, Texas. Horizon 1 is the structureless horizon, (has probably been plowed); 2 a heavy clay, faintly columnar, horizon with imperfectly developed granular structure, and 3, the carbonate zone. North Texas Division of the Black Belt.

In every region, whatever its character, the soil passes through a series of stages in its development from what may be called its infantile conditions to a condition that may likewise be designated as old. The infantile condition is represented by that existing in the parent soil material immediately after it has been accumulated in the place where it is later developed into soil. The features assumed by the soil in its development from infancy through youth, maturity and old age vary with the environment, especially with the climate and the natural vegetation. The broad general features assumed by the normal or mature soil will be uniform throughout any given climatic and vegetational region.

In its youth the character of the soil is determined by that of the parent geological material. As it advances in stage of development, geological features become less and less influential and "acquired" characteristics become more and more influential as determinants of soil character. At what may be designated as the mature stage in its development the character of the soil is dominated by acquired characteristics and the characteristics determined by those of the parent rock have disappeared or become subordinate; and this relationship continues to exist thereafter, though becoming progressively more and more pronounced. In the infantile stage of development the soil varies according to the character of the parent material and has no necessary relation to the character of the climatic and vegetational region in which it occurs. The soil character will not vary with the latter conditions, but with the former only.

At maturity however the "accidental" hit or miss characteristics of the parent rock have disappeared from the soil or have become very subordinate to those gradually acquired during development so that throughout a given climatic region the broad general features of the soil will have become uniform. Maturity may be defined as that stage in the soil development where its dominant features are those accquired during development and not those determined by the character of the parent rock and in which these features have attained an average degree of development and in no feature have attained an abnormal degree of development. The normal degree of development will be that characteristic of the majority of the individual soils, in the given region, which have lost their infantile features.

The rate at which soil development takes place in any given climatic or vegetational region varies with the topography and the texture of the soil material. If the latter be very heavy the rate will be slow and if very light it will be rapid. Where the material is intermediate in texture, as is the case with most soil materials, the rate will be

strongly influenced by the topography. The soil will attain maturity on the flat and gently rolling surfaces earlier than on the rough, and in fact it may never attain full maturity on the latter. As development proceeds, erosion removes the changed surface material so that the soil is being perpetually rejuvenated and a new soil is continually being formed by fresh material accumulated from the rock below by disintegration, or by the soil section moving gradually and continually downward into fresh geological material.

The topography of the Dakota Division is constructional, the stream valleys are shallow and free from steep slopes. There are no important areas in which the topography is rough enough to interrupt the normal course and rate of soil development. All the soils are submature or younger; this being indicated in ascribing some of their dark color to the character of the parent material, but they are all alike in this respect. Rendzinas are young soils, wherever they may be found.

In the area of the Kansas Division the topography is not as uniformly free from steep slopes as in that of the Dakota Division, but a relatively small percentage of the total area is rough. These rough surfaces are covered by immature soils, in which the profile is not normally or maturely developed, yet the percentage of total area is small. On such slopes however, the only feature of the mature soil profile of the region that has been developed is the dark surface horizon, and this has usually but a fraction of its mature thickness. By far the larger part of the area is smooth, and this is covered by soils that have reached a mature or normal stage in their development. Rendzinas are not present on these smooth uplands.

In the North Texas area however, a much larger proportion of the total area is rough enough to prevent the attainment of maturity by the soil. This explains the character of the soils of the area as shown in the typical profiles already described. The climate of this region is different from that in Kansas in a subordinate but significant way and effects the course of soil development in the same direction as the topography and emphasizes the effect of that factor.

The special climatic features are the prevailing high temperature with a correspondingly rapid evaporation of moisture, and the occurrence of the rainfall in sudden heavy downpours of short duration.

The characteristic features of the mature soil in the North Texas area develop therefore only on the poorly flat lands and not on the rolling lands. A considerably smaller proportion of the total area is covered by mature soils than in the Kansas or Dakota divisions. The map (Fig. 2) will give some idea of the proportion of the total area that is covered by the mature soil, the Abilene clay loam. This

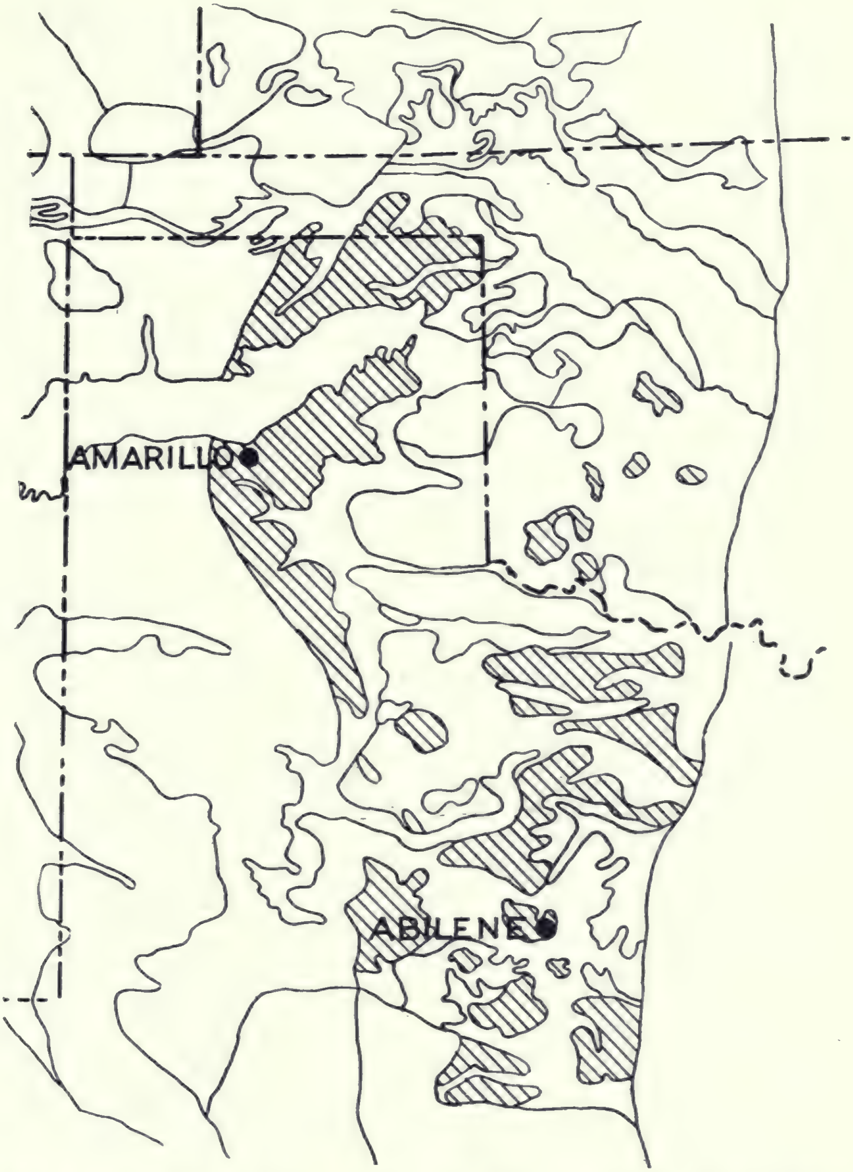


FIG. 2. The areas of mature soil with well developed profile in the North Texas Division of the Black Belt.

area has not been mapped, except in small spots here and there, so that the map given here is very much generalized and imperfect. It will be noted that a larger proportion of mature soil is found on the High Plains around Amarillo than in other parts of the area.

The development of the soil in sandy areas runs parallel with that on rough topography. A considerable area of sandy soil, and therefore of soil without the features of the normal or mature soil of the region, lies in Western Oklahoma. Profiles of the mature soil at Miami, Texas, and at Snyder, Texas are as follows:

Richfield clay loam, Miami, Texas.—

1. Dark brown granular clay loam............	0 to 12 inches
2. Brown clay with faint reddish shade, no noticeable granulation, breaks on drying to rough columns and irregular clods..............	12 to 30 inches
3. Reddish brown clay with lime carbonate concretions.	

Amarillo loam (or sandy loam) Snyder, Texas.—

1. Dark brown sandy loam with faint reddish shade, granular	0 to 12 inches
2. Dark reddish brown loam, cloddy............	12 to 26 inches
3. Reddish brown clay loam, cloddy............	26 to 34 inches
4. Highly calcareous horizon, loose, pinkish......	34+

The Edwards Division.—

This area covers the eastern part of the Edwards Plateau in Texas. It is a region of smooth plateaus separated by valleys varying greatly in width. The valleys may consist of narrow gorges or of broad lowland belts in which the actual stream valley is an insignificant feature. The location and distribution of the area is shown on the map Fig. 1.

The soils are all shallow and lie on limestones with the exception of insignificant belts of shales, always calcareous, and the larger area of the Llano basin where the soils overlie sandstone in part and granite in part. Throughout the whole region the soil has developed from material accumulated by the decay and disintegration of rocks similar to those on which it lies.

The soils are so shallow that the normal profile is rarely developed. It is only in especially smooth places that a normal profile is seen. One at El Dorado, Texas, is as follows:

1. Very dark brown to black clay loam..............	0 to 2 feet
2. Reddish brown clay	0 to 3 feet
3. Pinkish white carbonate zone, indurated to caliche in places. It varies rapidly in depth, ranging within a zone about a foot thick.....................	3 feet +

The most common profile consists of a few inches of black to very dark brown clay loam ranging up to 12 to 16 inches in thickness, becoming sometimes reddish in the lower part overlying a cap of accumulated indurated lime carbonate lying on and adhering to the underlying limestones. The dark color of the soil seems to be due, in part, as in the Dakota area, to the calcareous parent rock. The predominant soil therefore is immature, still retaining the influence of the parent rock. This gives it a darker color than the mature soil of the North Texas Division. It is therefore a soil with Rendzinas characteristics. Even in its most mature phases, as at El Dorado. it is darker than the normal mature soil of the region. On the valley slopes there is very little soil present, most of them consisting of limestone outcrops with pockets of dark colored soil here and there, or streaks and benches of gray soil consisting essentially of disintegrated gray calcareous shale.

The soil in the Llano basin is brown and since the area is rolling, consists mainly of reddish sandy clay with the carbonate zone undeveloped except on the relatively unimportant flat areas.

The Edwards area supports an open stand of scrubby trees, mainly oak. The older, larger trees stand singly, the younger in groups, giving a park-like character to the region. No trees grow on the Dakota or Kansas areas of the Chernozem belt but Mesquite trees grow on the North Texas area from the Red River southward; they do not extend on to the High Plains portion of the belt. Oak trees do not grow on the North Texas Division. The Edwards area is utilized almost exclusively for grazing.[2]

A relatively small area surrounding the town of Fredericksburg is used for general farming and the valley of the river above and below Menard is irrigated and used for growing general farm crops. The population is very sparse and is confined mainly to the few towns of the area. San Angelo, an important town, is the metropolis of the region.

The South Texas Division.—

The location and extent of the area, extending from San Antonio to Brownsville, Texas, are shown on the map Fig. 1. It consists of two sloping plains, one extending from the foot of the Edwards Plateau, westward from San Antonio, as a southeastwardly sloping plain to a few miles beyond the Nueces River; the other starting from the top of a rather poorly defined escarpment rising from the southern boundary of the northern plain and sloping thence southeastward to

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[2]. Dr. B. Youngblood. An Economic Study of a Typical Ranching Area on the Edwards Plateau of Texas. Texas Agr. Exp. Sta. Bul. 297.

the Gulf. A broad belt extending along the valley of the Nueces River to its southward bend and thence in the same direction to the boundary of the area marks the low part of the northern plain, the abruptly rising edge of the southern lying a few miles southeast of the river. The soils of the area vary to a considerable extent, the range in variation being expressed fairly well by the following profiles.

Five miles south of Floresville, Texas.—

1. Dull dark-brown sandy loam	0 to 10 inches
2. Dark reddish brown heavy sandy clay that hardens and cracks on drying, somewhat calcareous; cracks irregularly on outcrops	10 to 14 inches
3. Pinkish gray calcareous clay	14+ inches

Five miles south of Beeville, Texas.—

1. Dark brown sandy loam	0 to 10 inches
2. Reddish brown clay loam	10 to 24 inches
3. Pinkish gray mass of lime carbonate and clay with indurated lime carbonate crusts	24 in. +

Thirty-eight miles south of Falfurrias, Texas.—

1. Dark brown sand and loamy sand	0 to 12 inches
2. Grayish brown sandy clay	12 to 40 inches
3. Caliche	40+ inches

Three miles south of Kingsville, Texas.—

1. Black clay loam	0 to 12 inches
2. Gray clay calcareous	12 to 48 inches
3. Light gray to nearly white clay with abundant selenite crystals	48+ inches

The soils, where mature, are not black. The heavier and less mature soils are darkest in color. In all cases where mature soil has developed from sandy clay deposits the surface soil has become a sand, the clay being washed into the subsoil. Where the soil has been well drained for a long period and has rolling topography, the subsoil becomes invariably red, the carbonate zone becomes indurated to a caliche and is often many feet in thickness. On the other extreme of drainage and stage in development the surface soil is a very dark gray clay and passes downward within less than two feet to a gray calcareous deposit of late geological age. This is the Victoria clay, as mapped by the Bureau of Soils. It occupies a large area around Corpus Christi Bay.

The escarpment, forming the abrupt rise from the low southern border of the northern plain to the higher northern border of the southern plain is made possible by the outcrop, along its top, of the caliche horizon lying beneath the Duval soils which occupy the high

northern border of the southern plain. The Houston soils along the low belt of the northern plain are immature soils in which the carbonate zone has not yet become indurated or highly concentrated. These are not true Houston soils, the latter being true Rendzinas found in thoroughly humid regions. The soils mapped as Houston in this area however, are half Rendzinas and half Chernozorus somewhat like, in that respect, the Dakota Division soils and those of the Edwards Division.[3]

The Very Dark Brown Belt.—

The location and distribution of the belt are shown on the map Fig. 1 It is confined to the Dakotas. Future work in the region west of the Black Belt and south of the Dakotas may obtain data that will warrant extending it across the Plains from north to sonth. At present it cannot be done.

The soils so far as color is concerned are sufficiently described by the name applied to the belt. They are merely less black or less dark in color than those of the Black Belt.

The carbonate horizon lies a little nearer the surface than in the Black Belt ranging approximately between the depths of 24 and 30 inches.

The topography is essentially like that of the Black Belt except in the section that contains the Missouri River Valley. A narrow belt on each side of that stream consists of recently laid alluvium and of rough land along the river bluffs, the soils in both cases being immature, that feature expressing itself in the absence of the carbonate zone.

A narrow belt along both sides of the several small rivers and creeks entering the Missouri from the west is of the same character. This incledes the narrow belt of "bad lands" along some of these streams. West of the Missouri in South Dakota the parent rock is a fine grained shale. The glacial deposits are in most cases very thin and where present consist mainly of shale material. The soil is very heavy therefore, and in such conditions the rate of soil development is very slow. Even on the ridge tops in this region the soil is often quite shallow and the carbonate zone has not developed.

Considerable areas of soils with heavy tough clay subsoils, similar to those occurring in Beadle County, South Dakota, lie in the vicinity and west of Highmore, and between Blunt and Pierre, South Dakota.

[3] Reconnoissance Soil Survey of South Texas, Field Operations of the Bureau of Soils for 1909 and Reconnoissance Soil Survey of Southwest Texas, Field Operations of the Bureau of Soils for 1911.

In considerable areas in North Dakota, in McHenry County, especially, the soils are very sandy.

The Dark Brown Belt.—The general distribution of the belt is shown on the map Fig. 1. The soils are dark brown to dark reddish brown, less dark in color in all latitudes than the soils of the Black Belt in the same latitude.

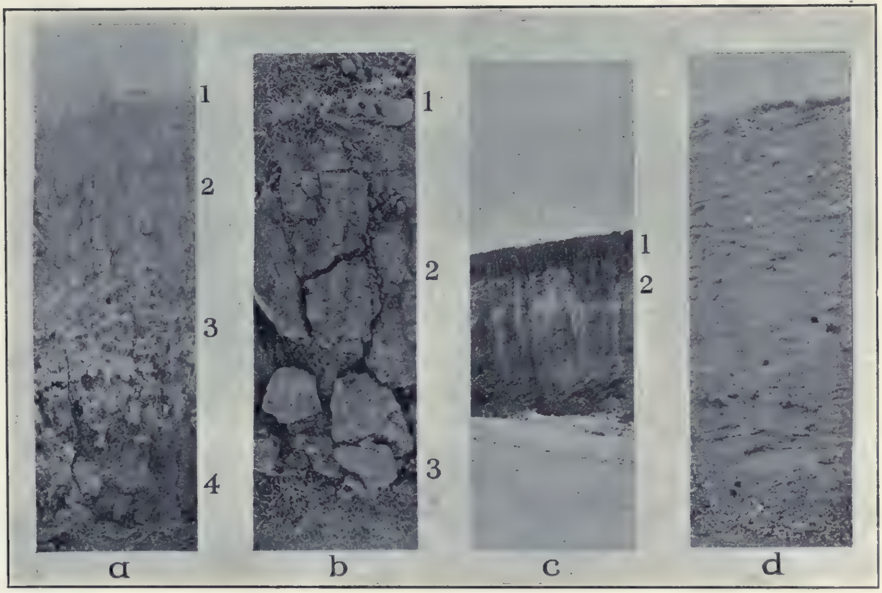
The carbonate zone lies at shallower depth than in the Black or Very Dark Brown belts to the east, ranging from 12 to 24 inches. The horizon of perfect granulation so well developed in the Kansas Division of the Black Belt, but less perfectly developed elsewhere, seems to be absent from the soils of the Dark Brown Belt*. For convenience of description and on the basis of slight variation in color and other features of less importance the whole belt may be divided into three areas; Northern, Central and Southern Divisions respectively.

The Northern Division.—The location and area are shown on the map. The mature soil of the region occurs in a series of isolated areas varying greatly in size, instead of in one unbroken or very nearly unbroken area, as in the Dakota Division of the Black Belt. This is due to a considerable area of rough land and bad lands caused by the dissection to which it has been subjected. Broad belts of such lands lie along both sides of the Yellowstone, the Little Missouri, the Cheyenne, the Missouri, the Powder and Tongue rivers and smaller belts along the smaller streams. No such belts traverse eastern North Dakota and the streams traversing the Kansas Division of the Black Belt are less effective in reducing the upland area of mature soils than in that region. All these hilly belts are covered with a shallow soil in which the normal profile has not become uniformly or generally developed. They include innumerable small areas without regularity of distribution in which the soil is mature, but these areas are not large individually or in total area.

While the typical mature soil has been described as dark brown, the belt as delineated on the map, extends far enough westward to include soils that are predominantly much less dark than those in the eastern part of the belt. This is especially true of the soils along the Milk River Valley, of those between the Missouri and the Yellowstone and of those in Eastern Wyoming and southwestern South Dakota.

The Black Hills area introduces a group of foreign soils into the area, the greater part of them consisting of light colored timber soils

*This statement is true in general. The horizon seems to be imperfectly developed along the eastern border of the belt in Kansas, as the boundaries are now placed. It may be found advisable in the future to place the western boundary of the Black Belt farther west than at present, and possibly along the western boundary of the granular horizon.



a. Profile at Glasgow, Montana. Horizon 1 is structureless and thin; 2 is columnar; 3, the carbonate zone, and 4, the parent material, calcareous but less so than horizon 3. Dark Brown Belt.

b. Section of soil removed from a roadside excavation and photographed in a horizontal position. Horizon 1, very thin, is structureless; 2 is columnar, rather imperfectly so and 3, is the carbonate zone. Dark Brown Belt in southwestern Kansas.

c. Deep road cut near Akron, Colorado. Dark Brown Belt. Shows the carbonate zone indurated to a caliche.

d. Railroad cut ten miles west of Santa Rosa, New Mexico, showing caliche immediately beneath the surface. The fragments are those of caliche and not of limestone. Brown Belt.

similar to those in northern Minnesota and Wisconsin, but this central area is surrounded by a more or less continuous but narrow band of Black Earth and this in turn by a still less continuous belt of Very Dark Brown Soils..

The typical medium textured soil of the area has a profile about as follows:

Profile of Mature soil, Dickinson, North Dakota.—

1. Brown structureless light loam.............	0	to	2½	inches
2. Dark brown somewhat granular loam........	2½	to	9	inches
3. Brown loam	9	to	14	inches
4. Loose structureless, carbonate zone..........	14+			inches

Soils of this general character prevail southward into northern south Dakota. South of that in South Dakota, Nebraska and southeastern Wyoming, the soil is heavy, though the profile is usually well developed. In northeastern Wyoming and southeastern Montana the soil is about as dark in color as at Dickinson, but the surface horizon is somewhat lighter in texture. The individual areas are narrow, separated by belts of rough land with immature soils.

Along the Milk River, around Jordan and Miles City, Montana, there are many " Slick Spots " or " Buffalo Wallows " or "Blowouts " consisting of small areas ranging up to 30 feet in diameter, bare of vegetation, depressed usually about five inches below the surrounding area, the surface of the basin consisting of a heavy tough clay. The clay horizon ranges up to a foot in thickness, below which lies friable clay or lighter textured material. The clay bed and material below usually contain salt segregations and gypsum crystals. These spots may be thickly or thinly sown over an area. They occur mainly on level or in slightly depressed situations. They seem to be essentially like the soil with heavy subsoil described from Beadle County, North Dakota and elsewhere, in which the clay horizon is locally developed in spots and from which the lighter soil above has been blown away. They may be seen in all stages of development from the Beadle County type to the fully developed " slick spot."

A western outlier of this division of the Great Plains soils covers the area of the Judith Basin in Fergus county, Montana. It consists of a lowland, roughly circular in shape, surrounded discontinuously by mountains, none of them very high but all high enough to promote the formation of summer thunder showers. The influence of the mountains extends over the basin, over the low belts between the links of the encircling chain of mountains and a narrow belt surrounding the mountains on the plains outside. The basin has been filled to a

depth of many feet by a series of alluvial fans spread out toward the center from the surrounding mountains. Similar fans are built outward on the plains from the outer slopes of the mountains. The gravel of which the fans are built contains a significant to large percentage of limestone pebbles. The soils developed from these deposits are somewhat like those of the Dakota and Edwards Divisions of the Black Earth belt to the extent that they are darker in color than they would be were the parent material less calcareous or were the soils more advanced in their stage of development.

The soils are universally shallow, it being often less than two feet to the unchanged parent gravel beds. A section measured in an excavation on the Experiment Farm at Moccasin, Montana is as follows:

1. Brown, loose structureless heavy loam (Plate II, b and c)	0 to 3 inches
2. Dark brown, somewhat granular clay loam	3 to 10 inches
3. Yellow brown clay loam	10 to 20 inches
4. Carbonate horizon	20+

As the mountains are approached in any direction from a point in the basin the soils become darker, first very dark brown and finally black, then changing rapidly as the timber covered slopes of the mountains are reached to light colored typical woodland soils. The same series of belts may be crossed in approaching the mountains from the plains outside the basin. The belts are usually narrow however, and are not developed where the topography is not smooth.

Narrow belts of similar character lie along the Rocky Mountain Front. The eastern part of each belt has dark brown soils. Westward the soils become darker and in places there are areas of narrow strips of true Black Earth lying directly under the mountain front. The soil just east of Glacier Park Station on the Great Northern Railway seems to be of such a character. South of this the belt in which are situated the towns of Valier, Conrad, Dupuyer, Chouteau, Fairfield and Augusta, Montana, is covered with soils of dark brown color; the color running somewhat lighter than at Dickinson, North Dakota, and darker than on the upland between the Yellowstone and the Missouri. Similar soils are known to lie along the mountain front east of the Crazy Mountains, and the Red Lodge Country, along the east foot of the Big Horn Mountains, and the Rocky Mountain Front between Denver and Colorado Springs. They seem to be present locally between Raton and Las Vegas, New Mexico.

The part of the Northern Division lying in North Dakota, except the southwest corner, and the adjacent part of Montana, especially the

region around Wibaux has been developed into a wheat growing region of no importance. The same is true of a belt along the Canadian border from the eastern boundary of the state westward into Blaine county, Montana. In South Dakota most of the area is utilized for grazing.

The Central Division.

The location and extent of this area are shown on the map (Fig. 1). The area is smoother than that of the Northern Division. It is crossed by the North Platte, the South Platte and the Arkansas. The North Platte is the only stream along which any considerable belt of rough or bad land topography has been developed. In most of the area therefore, the soils are approximately mature except for the areas of sands of which there is a much larger area than in the Northern Division. Sands have a very restricted distribution in the latter area.

The soils, as a whole, are somewhat lighter in color than in the typical area of the Northern Division, the carbonate zone ranges around 16 to 20 inches in depth and the granular horizon, as further north, seems to be lacking.

The character of the soil of intermediate texture is shown by the following profiles.

Profile at Dalton, Nebraska.—

1. Medium dark brown loam	0 to 4 inches
2. Brown loam, imperfectly cloddy	5 to 14 inches
3. Loose calcareous horizon	14+ inches

Profile at Akron Experiment Station, Akron, Colo.—

1. Brown silty loam, defloculated, showing a pronounced horizontal or layered arrangement in natural position	0 to 8 inches
2. Dark brown, columnar clay or clay loam, compact rather hard when dry, columns half an inch to an inch in diameter, each having well defined horizontal breakage	8 to 16 inches
3. Gray loose, highly calcareous material	15+ inches

Profile nineteen miles north of Elkhart, Kansas.

1. Loose brown loam, structureless	0 to 4 inches
2. Brown clay loam, faintly granular, dark shade	4 to 12 inches
3. Yellowish brown clay loam	12 to 15 inches
4. Yellowish brown clay loam, calcareous	15+ inches

Profile three miles west of Two Buttes, Colorado.—

1. Brown clay loam, dark shade, somewhat granular.	0 to 8	inches
2. Brown clay loam, cloddy..................	8 to 11	inches
3. Calcareous horizon	11+	inches

Not including the sand hills, the mature soils of the area do not vary widely. Areas of sand occur on the plains west of Alliance, Nebraska, in the region of Wray, Colorado, east of Sugar City, Colorado, and along the Arkansas.

The part of this division lying between the two Platte Rivers in Nebraska, has been utilized for agriculture more completely than any other part. though a great deal of northeastern Colorado and northwestern Kansas is about equally as fully used for crop growing, mainly wheat. The western part of the area is not used extensively for crop growing anywhere. This statement does not apply to the irrigated regions in the valleys of the two Platte Rivers in Wyoming, Nebraska and Colorado.

The profile at Akron, Colorado, represents one of the two profiles that prevail throughout the area of the Central Division and that at Dalton, Nebraska the other. The former shows the extreme development of this profile. Its characteristic features are the light colored, loose defloculated surface horizon and the darker colored, more compact subsurface horizon with well defined columnar breakage, below which lies the carbonate horizon with or without an intermediate lighter colored horizon. The extreme development of this profile at Akron is shown in the 8 inch thickness of the surface horizon and in the extreme development of the columnar breakage of the subsurface horizon on outcrops. Throughout the greater part of the area of the division the thickness of the surface horizon will range around one to two inches. The columnar breakage in the subsurface horizon is less well developed as a rule, the columns are larger, the shape less uniform, the surface less smooth and the horizontal breakage much less perfect.

In the Dalton profile the differentiation into the gray horizon and the columnar subsurface horizon is not strongly developed. There is some imperfect development of the latter but the former is not noticeable, while the total thickness of the two (or three) horizons above the carbonate horizon is greater than in the other types.

It seems that the Dalton type of profile is more prevalent in the northern and eastern, especially the latter, parts of the area while the Akron type is prevalent in the western part but not usually in extreme form. The latter is prevalent over the former. Both types of profiles are as characteristic of the Northern Division as of the Central.

The Southern Division.—

The location and area are shown on the map (Fig 1). The lines between the Black Belt and the Dark Brown Belt and between the latter and the Brown Belt as they have been located on the map are based on a smaller amount of actual information than is true of most of the other boundary lines. While it is true that they are all based on incomplete information and are liable to more or less change in the future, it sems probable that the boundary lines in western Texas and in New Mexico will be subjected to greater changes than elsewhere. Both the eastern and western boundaries of the Dark Brown Belt must be regarded therefore as even less definitely established on the ground than are the others.

The characteristics of the soil in the western part of the belt as now defined are shown by the profile measured at Dalhart, Texas, and those on the eastern side by the profile at Big Springs, Texas.

The soil profile at Dalhart, Texas, a profile that may be considered representative of the northern portion of the area is as follows:

Profile one mile southwest of Dalhart, Texas.—

1. Brown structureless loam..................	0 to 1½ inches
2. Dark brown heavy loam, somewhat granular..	1½ to 7 inches
3. Pinkish brown loam.........................	7 to 15 inches
4. Pinkish yellow highly calcareous clay loam, loose	15+ inches

Profile seven miles south of Big Springs, Texas.

1. Dark brown loam.........................	0 to 5 inches
2. Dark reddish brown heavy loam............	5 to 18 inches
3. Light reddish brown loam, with yellowish shade	18 to 34 inches
4. Pale pinkish loose calcareous horizon with hard calcareous concretions	34 inches +

The profile at Big Springs shows a soil a good deal darker in color than that at Dalhart. The zone of carbonate accumulation is deeper and the subsurface zone is less columnar in its breakage on outcrops. The latter characteristic is more typical of the soils of the Dark Brown Belt than is the profile at Big Springs, while that at the latter place is more like the profile in the Chernozem than is that at Dalhart. Further investigation may show that the western boundary of the Chernozem belt (The Black Belt) should run west of Big Springs.

The southern part of the area, except the extreme southern part, is occupied by a westward extension of the Edwards Plateau and could be separated from the rest as a distinct division as was done in the case of the Black Earth belt. This has not been done in this belt because of the lack of definite information regarding the soils. It is known that

the soils are shallow and underlaid by a pinkish carbonate zone or by limestone, but whether the limestone is capped by a thin caliche, or not, is not known. The color of the soil is not known, though such information as is available indicates that it is lighter in color than the soils of the Black Earth Belt.

In the western part of the area in Texas, however, there are many square miles of sandy soils. In some cases the sands are several feet thick, in others thin, the underlying red clay or sandy clay appears at three feet or less. A belt of sandy soils lies between Seminole and Lamesa, Texas, and extends southward many miles. Another lies between Lubbock and Clovia, and another between Clayton, New Mexico and Dalhart, Texas. Considerable areas lie in the Oklahoma panhandle.

Grazing is the predominant industry, almost the exclusive one on the western area. On the eastern area considerable crop growing has developed locally, especially in the vicinity of La Mesa, Big Springs and along the eastern border. Cotton and sorghums are the predominant crops.

The Brown Belt.—

This is a discontinuous belt, broken up into several separate parts, the location and extent of each being shown on the map (Fig. 1.) The soils of this belt are the lightest in color of all the Great Plains soils and the carbonate zone beneath them is shallowest. The color of the soil is brown rather than distinctly dark brown, but, as compared with the lighter colored soils of the deserts, it may be placed, with sufficient justification, with the dark colored soils. Like the other Great Plains soils it has developed under a grass cover but one of somewhat less dense growth than on the other belts. These soils, where the belt in which they occur is not bounded on its western side by the mountains or by the "Mountain foot" belt of darker colored soils, change westward by imperceptible gradations into the still lighter colored soils of the deserts.

A typical profile of the soil in the northern area, sampled a few miles south of Chester, Montana, is as follows:

Profile ten miles south of Chester, Montana.—

1. Light brown loose deflocculated loam............ 0 to 2 inches
2. Brown clay loam.......................... 2 to 12 inches
3. Grayish highly calcareous clay loam.......... 12+ inches

A number of samples collected from various localities in this area show the color and depth to the carbonate zone to be quite uniform.

"Slick Spots" are of common occurrence in many parts of this area, the most abundant seeming to occur from the Milk River, a few miles west of Havre, southward to the Marias River. Another area lies in the flat land area in the vicinity of Shelby, Montana, and a string of them extends down the Milk River valley from Havre to Malta, though these lie mainly within the belt of Dark Brown soils. Areas of soils with high content of alkali salts also occur in the vicinity of Shelby.

This area is continued by a very narrow belt running southward by way of Sheridan, Wyoming between the Big Horn Mountains on the one hand and the elevated plateaus east of Sheridan on the other. South of Sheridan it widens to include most of eastern Wyoming. The soil in the eastern part of the area is somewhat more sandy and apparently also less naturally developed than in the western part, excepting on areas in the vicinity of Caspar. The soils are brown and the carbonate horizon lies about 12 to 15 inches beneath the surface.

The Colorado area varies considerably in the character of its soils. In the northern part the soils are very much like those in the northern area, becoming a little reddish just above the carbonate horizon. A profile measured near Wild Horse, Colorado is as follows:

Profile three miles east of Wild Horse, Colorado.

1. Light brown loam loosely defloculated........	0 to 6 inches
2. Brown loam, darkish shade, columnar breakage on drying	7 to 17 inches
3. Gray calcareous zone......................	17+ inches

In the southern part of the area the grass cover is less dense than anywhere else east of the mountains and the vegetation assumes an appearance approximating that of the desert vegetation. The soils are still lighter in color except where dominated by the color of the parent rock, a brown shale, and the salt content is sufficient to cause the development of a rather well defined alkali profile. A profile measured at Avondale, Colorado is as follows:

Profile three miles northeast of Avondale, Colorado.—

1. Light brown loose structureless sandy loam....	0 to 3 inches
2. Brown sandy clay loam columnar breakage....	3 to 13 inches
3. Gray loose calcareous material................	13+ inches

The soils of the Brown Belt between Raton and Las Vegas, New Mexico seem to be darker in color than those in the Colorado part of the belt. Our knowledge of the characteristics of the New Mexico portion of the belt is very defective. It has been traversed but once,

this traverse running from Raton by way of Springer and Wagon Mound to Las Vegas. The eastern part of the area is practically unknown.

The route from Raton to Las Vegas lies but a short distance east of the mountains and the soil is probably darker than it is further east. On account of this probability no attempt has been made to give this area any special designation on the map. That part of the Brown Belt lying south of Las Vegas, extending at least as far south as the south line of New Mexico has a well defined *caliche* (Plate II,d) or indurated carbonate zone lying at a very shallow depth. In a large part of the area it is barely covered with soil and in others it lies on the surface, there being practically no soil except what lies in depressions in the surface of the caliche. The soil in many places seems to be little else than a product of the decomposition of the upper part of the caliche. In other places such soil as is present consists of accumulations of blown sand. The sand is especially abundant on the bench on the east side of the Pecos river south of Ft. Sumner and on the western escarpment of the High Plains lying approximately half way between the Texas line and the Pecos river. Between the top of the escarpment and the western line of the Dark Brown Belt the soil is not sandy as a rule, but it is shallow.

The Pecos River from a few miles south of Ft. Sumner New Mexico, flows southward through a region that becomes more and more desert-like in its features southward until in the Tova basin around Pecos, Texas, the desert characteristics dominate every other. It is possible that future study may obtain data that will warrant the extension south of Roswell and thence eastward between the Teyah desert on the west and the Dark Brown belt on the east. Such a belt if it exists, may include the western and the Edwards Plateau, from Sanderson westward.

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THE CLIMATE OF THE GREAT PLAINS AS A FACTOR IN THEIR UTILIZATION

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Introduction. A number of geographic factors, principally climate, topography, and soil fertility, operating either separately or in varied combinations, influence agricultural conditions. Of these, climate is the most fundamental, unalterable and important, not only in influencing the distribution of particular crops, but also in determining the suitability of land for agricultural purposes. The land surface of the earth may be classified broadly as potentially agricultural and non-agricultural. The potentially agricultural land may be designated as productive and non-productive, and the former subdivided according to suitability for crops, pastures, or forest, based largely on climatic conditions.

Agriculturally, the United States is one of the most favored countries of the world. Large areas of its land surface are potentially agricultural, with climatic conditions favorable for crop growth, particularly in the eastern half of the country. In the west, however, much of the land is semi-productive, as the climatic elements do not occur in the best combination to favor intensive cultivation. Precipitation is usually the limiting factor. The most important single area to be classed as semi-productive is the region of the Great Plains lying just east of the Rocky Mountains.

Moisture Limitations.—*Annual Precipitation.*—By selecting crops with the proper thermal requirements, each staple crop produced in the United States could be grown with profit in some section of the Great Plains, so far as temperature is concerned. The agricultural utilization of the region, however, is limited by moisture conditions, especially

in the central and southern portions. There is a gradual decrease in the average annual precipitation from more or less humid conditions in the east, to semi-arid, or even arid, in the west.

Figure 1 shows that the average annual precipitation ranges from 20 inches in extreme eastern North Dakota, to 25 inches in south- central South Dakota, central Kansas, and west-central Texas and Oklahoma, to less than 15 inches in much of Montana, eastern Wyoming, eastern Colorado, and the Brazos Valley in western Texas and eastern New Mexico. The minimum precipitation in the area is about 6 inches, in the Bighorn Valley of Wyoming. In the vicinity of Hyatville in this valley the average precipitation for a 12-year record is only 4.5 inches, and in 1921 only 3 inches fell.

The chart shows that there is a rather uniform diminution of precipitation from the eastern to the western portions of the Plains, except in Montana. The central and eastern portions of this State have a more diversified topography, thus a greater variation in rainfall than other portions of the Great Plains area. Where the surface is more or less uniform, as in the Yellowstone, Missouri, and Milk River valleys, trending in a general east-west direction, we find correspondingly small variations in precipitation, the amounts being nearly the same in all of these valleys, ranging mostly between 12 and 14 inches. There are some localities in the vicinity of Chester, Mont., where the annual precipitation is only slightly more than 10 inches. Southeast of these, in the Little and Big Belt Mountains, the amounts exceed 20 inches: a record covering 7 years shows an annual average amount of 30.24 inches near Garneille, in a pass between the Little Belt and Big Snowy Mountains, the greatest amount, except for some very short records, shown for any station in Montana east of the Rockies.

The minimum amount of annual precipitation necessary for successful farming by ordinary methods is usually considered to be between 15 and 20 inches. With an annual rainfall of less than 15 inches, other conditions must be very favorable to ensure successful crop production.

Much of Australia is similar to the Great Plains area in moisture conditions. In considerable portions of the winter wheat belt of Australia, dry-farming methods of fallowing and tilth are practiced extensively, and only one-third of the area is under wheat at a time. The determination of dry-farming areas there, depends principally upon the rate of evaporation. In some regions areas receiving less than 18 inches of rainfall are classed as dry, while others are so

classed when the rainfall is nearly 25 inches. It is considered that every 3 inches of free water surface evaporation requires 1 inch of rain in addition as an offset.

FIG. 1. Average annual precipitation over the Great Plains and adjoining sections.

In the Great Plains the agricultural significance of the rainfall depends principally on its seasonal distribution, the variations in amount from year to year, and the rate of evaporation. All of these modifying factors operate more favorably in the northern half than in the southern. The result is, that while rainfall is scantier in the north, conditions there are climatically more favorable for crop growth than elsewhere in the region.

Seasonal Distribution.—In the Great Plains, it is the rainfall of the crop growing season with which the farmer is mostly concerned. While the moisture stored in the soil at the beginning of spring is important, the amount is generally small, owing to the scanty winter precipitation, and therefore crops must depend largely on spring and summer rains. While the annual rainfall is light, the seasonal distribution is very favorable for the fullest utilization of the moisture received, particularly in the northern portion of the region. Winter precipitation is very light, less than ten percent of the annual amount occurring in most of the central and northern portions during the three months from December to February. With the advance of spring the amount increases rapidly. In Montana and the Dakotas, May and June are usually the months of greatest rainfall, while elsewhere, May, June, and July are about equal, except in western Texas and eastern New Mexico, where July leads.

Figure 2 shows the average warm season rainfall, April to September. It indicates that the amounts during this period of the year vary from 18 inches in northwestern Minnesota, extreme southeastern North Dakota and eastern South Dakota to less than 9 inches in parts of north-central Montana, and to less than 6 inches in north-central Wyoming. Farther south, the amounts range from 24 inches in the eastern portions of the Plains States to about 12 inches near the eastern foothills of the Rockies.

In the eastern half of North Dakota and much of northern South Dakota, more than 80 per cent of the annual precipitation occurs during the six warmer months of the year, April to September, and over practically all other parts of the area between 70 and 80 per cent occur during that period. In the Dakotas approximately half of the average annual amount is received during the three summer months.

Rainfall Variability.—When the average amount of precipitation borders on the minimum required for crop production, as is the case in much of the Great Plains, the variation from year to year, becomes of very great importance. In general, there is less than the normal amount of rainfall in more than half the years. In the northern portion of the Plains, the annual variations are comparatively small,

which is favorable to permanent agriculture, but in the south they are large, and less favorable, and rainfall is more frequently of a torrential character.

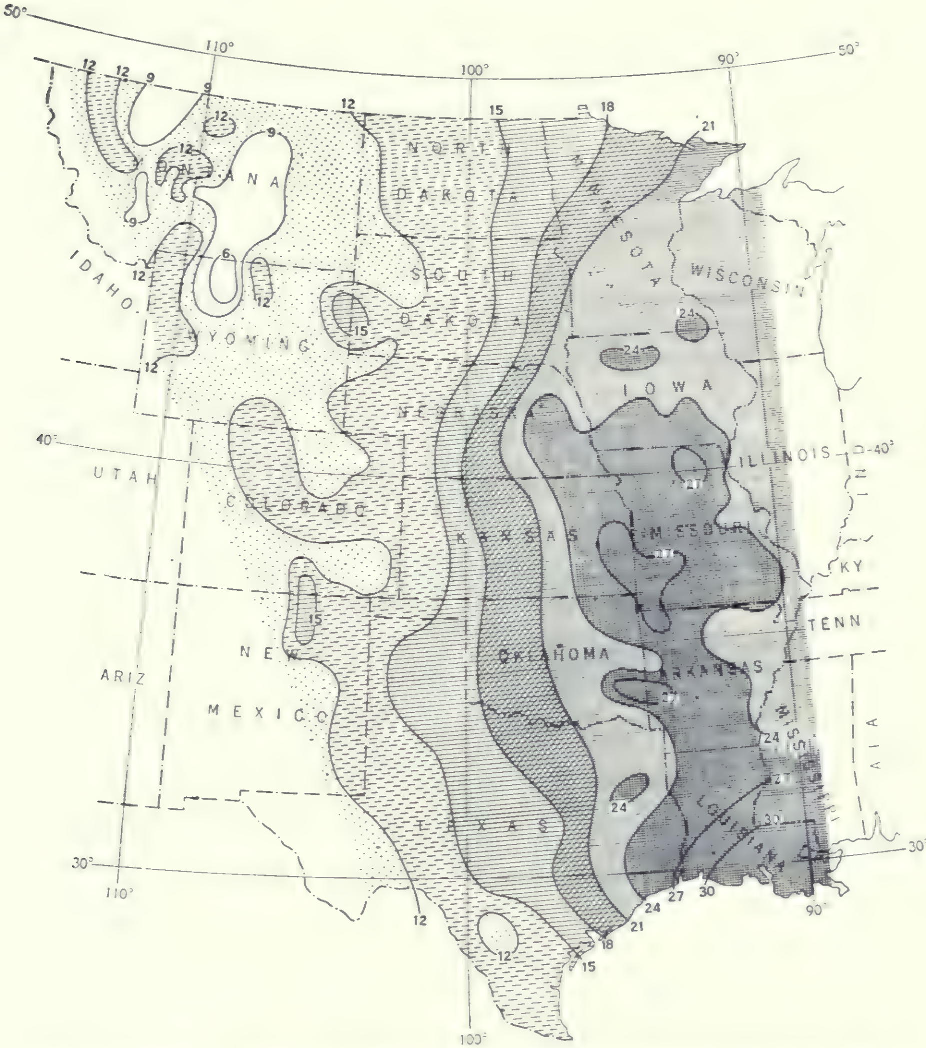

FIG. 2. Average warm season precipitation (April to September, inclusive) over the Great Plains and adjoining sections.

There is a well recognized tendency for precipitation in the Plains region to show several successive years of comparatively generous rainfall, followed in turn, by several years with deficient moisture, and this renders farming by ordinary methods precarious in many of the drier western portions of the section. Abundant crops in years of ample moisture encourage the western extension of the cultivated area, but the records show that these are only temporary conditions, and are likely to be followed by years of drought when the rainfall is entirely insufficient to mature crops. Disaster is sure to follow unwise agricultural adventures of this kind.

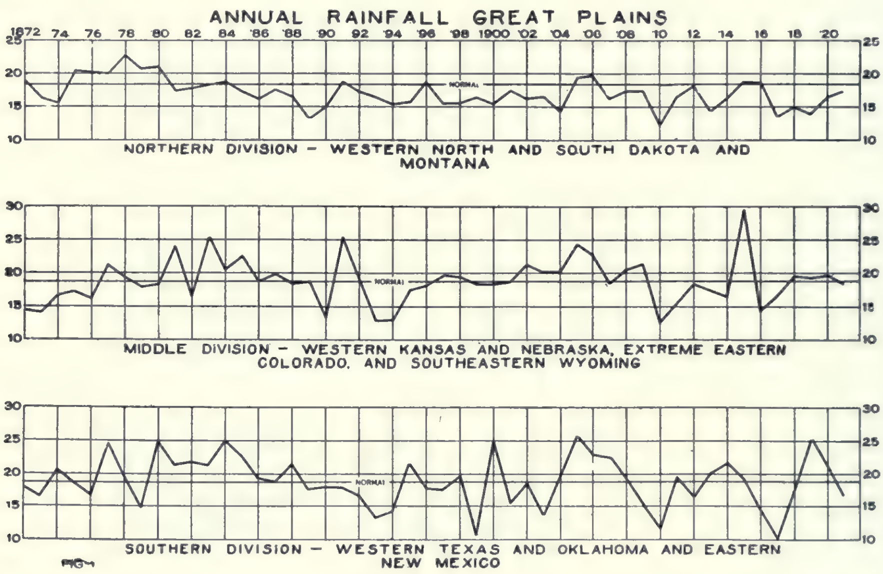

FIG. 3. Graphs showing variations in annual rainfall for a period of 50 years for the northern, central, and southern sections of the Great Plains region, each based on 12 to 20 rainfall records well distributed over the sections.

Figure 3 shows the variation in annual rainfall for a period of 50 years for the northern, central, and southern sections of the region, each based on 12 to 20 long-record stations well distributed throughout the area. These data show tendencies for comparatively humid and dry years to occur in groups, but without dependable regularity. They offer no evidence that rainfall is either permanently increasing or decreasing in any section. The fact is emphasized, however, that, while the average rainfall is somewhat lighter in the northern portions it is more dependable and therefore more favorable for stable agricultural enterprises. It will be noted that a three year period from 1917

to 1919 in the northern Plains had the greatest accumulated deficiency in rainfall shown for the entire 50 years of record.

Evaporation.—The rate of evaporation of moisture from the soil depends principally on the temperature, relative humidity, wind movement, soil composition, and the amount of moisture present. The increase in the rate from north to south over the Great Plains is pronounced. The warm season pan evaporation in the northern portion is slightly more than 30 inches as compared with about 60 inches in the south. The agricultural significance of these data, stated in terms of actual equivalent rainfall for the different areas, can be determined only approximately, since the variation in soil texture, the seasonal distribution and more torrential character of precipitation in the south, as compared with the north, introduce modifying factors not susceptible of direct quantitative evaluation.

It is probable, however, that the difference of 30 inches in evaporation between the north and the south is equivalent to about 10 inches of annual rainfall. The 20-inch annual isohyetal line conforms roughly to the 100th meridian of longitude, although its northern end extends farther east. In the Dakotas, the region through which it passes is largely devoted to crops, but in Texas, the land is mostly given over to grazing. In fact, one of the most important wheat producing sections of the country is found in eastern North Dakota, with an annual precipitation of about 20 inches.

Snow and Hail.—The average annual amount of snowfall ranges from about 30 inches in the Dakotas to 10 inches in extreme northern Oklahoma, but drops to 1 inch in southwestern Texas. Owing to low temperatures, the snow in the north is usually very dry, however, with a low water content, and frequently is drifted badly by high winds. The average annual number of days with the ground snow-covered drops from 120 in the extreme north to about 10 days in central Oklahoma. Hail is comparatively frequent in much of the region, particularly in the west-central portion where about 3 hailstorms occur usually at each point of observation during the growing season. In the extreme north and extreme south hail occurs, as a rule, on only one or two days, and is seldom experienced in the extreme lower Rio Grande Valley. These data, however, include all occurrences of hail, regardless of its severity, while it frequently occurs with little or no damage resulting.

TEMPERATURE.—Temperature conditions vary greatly in the Great Plains States. The physical aspects of the region are such as to favor normal latitudinal variations, typical of interior continental climates. Important local variations in temperature, due to topographic influ-

ences, are in evidence, but these are not the dominating temperature controls. Owing to its location in the center of the continent, far removed from marine influence, and the absence of transverse mountain barriers, the region is subject to pronounced changes in temperature, particularly in winter. The range from north to south is large. In general the winters in the northern half are frequently severe, sometimes with long periods of abnormally cold weather and at other times with rapid changes from day to day.

Figure 4 shows that the mean winter temperature in the extreme northeastern portion of the region is slightly above zero, with a rather uniform increase southward and southwestward. The increase over the Dakotas averages one degree for about 33 miles, but farther south it is somewhat less rapid. The range from the northern to the southern portion of the region is about 50°. Very low temperatures sometimes occur in the central and northern portions of the region. At some time during an average winter the temperature may be expected to fall as low as 40° below zero in northwestern North Dakota, 25° below in western South Dakota, and 10° below in southwestern Kansas, but no official sub-zero records have been made south of the 31st parallel in southwestern Texas.

As a further indication of winter temperature conditions in this region, it may be said that freezing weather, or colder, should be expected on slightly more than half the days in the year in eastern Montana and most of North Dakota; on more than 150 days in west-central Nebraska, 125 days in southwestern Kansas, and 40 days in west-central Texas, but freezing occurs on less than 10 days in the year in the extreme lower Rio Grande Valley. Freezing temperature has occurred in every month in the year in part of North Dakota, and zero, or lower, usually occurs on 50 to 60 days in the extreme northern portion of the Plains region.

While severe winter weather may be expected in the Great Plains, with cold, northerly winds reaching well into western Texas, much of the winter season is dry and bracing, and not uncomfortable for outdoor operations. Along the foothills of the Rockies, the cold is often markedly modified by the familiar warm, "Chinook" winds, and the western border of the region in winter is usually warmer, despite its greater elevation, than the sections farther east. In summer, the higher temperatures occur in the east. Chinook winds are of greater frequency in the more northern portions of the Plains area just east of the Mountains. They are of irregular occurrence and vary greatly in effect. They may begin when the weather is very cold, or with moderate temperature, and may be widespread or very

local. At times they cause a rise in temperature of 50° or more within half an hour and again the rise may be only 5° within an hour.

With the advent of spring, the warming-up is rapid, and much more so in the northern portion than in the southern, due largely to the more rapidly increasing length of days in the north. During

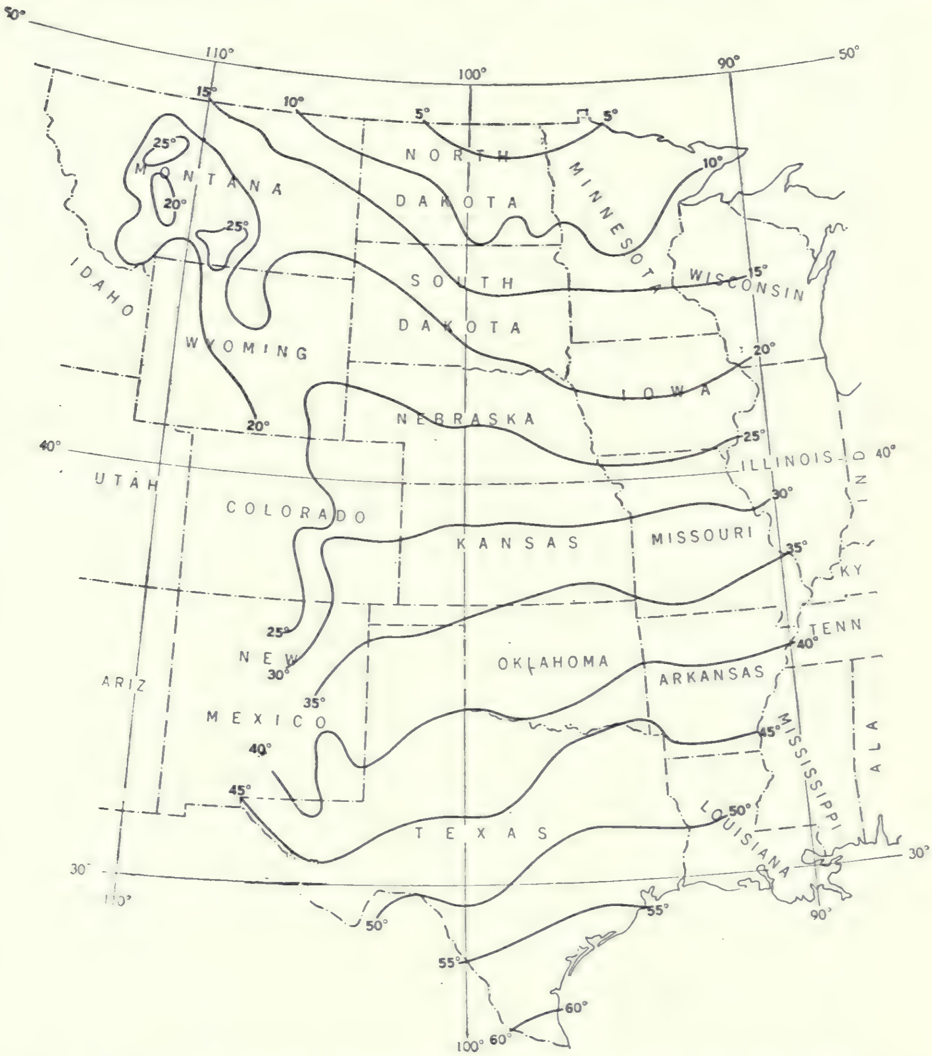

FIG. 4. Average winter temperature (December-February) over the Great Plains and adjoining sections.

March and April, the successive days become longer (sunrise to sunset) at an average rate of about three and one-third minutes in central North Dakota, and about half that number in west-central Texas. During this period, the increase in the daily normal temperature is at the rate of about 1° for each 6 minutes of increase in the day's length throughout the region.

Summer Temperatures.—Figure 5 shows that the summer temperatures in the Great Plains are much more uniform than those of winter. The average summer temperature ranges from about 65° in the extreme north to more than 80° in the south. The daily temperature range is large in summer, especially in the north, the average over much of the region being about 30° compared with 20° to 25° in the Mississippi Valley and 12° to 15° along the west Gulf coast. Periods of high temperature are comparatively frequent and are likely to accompany droughty conditions, while "hot winds," characteristic of this region, sometimes prove disastrous to vegetation. From western South Dakota and northeastern Nebraska northward to the Canadian border there is a noticeable absence of the usual decrease in temperature with increase in latitude, due largely to the lower elevation in the north.

Frost and the Growing Season.—The northward advance in spring of the average frost-free date line requires nearly three months, starting from the lower Rio Grande Valley about the first of March and reaching the northeastern part of Montana by the latter part of May. The advance is approximately at an average rate of 20 miles a day from west-central Texas northward. In general, the recession in fall is a counterpart of the spring advance as to rate and time required. The average date of the first killing frost in fall in the extreme northwestern portion is about September 10, and nearly three months later the frost line has receded to the southern border of the region.

Figure 6 shows that in the extreme northern portion of the region the average length of the frost-free season (from the average date of last killing frost in spring to the first in fall), ranges from 100 to 120 days. This increases to 160 days in east-central Nebraska and central-western Kansas, and to 200 days in northern Oklahoma and northwestern Texas. In southern Texas more than 260 days of the year, on the average, are free from frost.

The spring advance and fall recession of the average frost date line are comparatively uniform, the isochrones maintaining in general an east-west direction, but inclined from southwest to northwest. The more important sections that are favored by earlier springs and later falls and, consequently, longer growing seasons than normal for the

latitude, are the Pecos River Valley in southwestern Texas and eastern New Mexico, the Red River Valley in northern Texas and southwestern Oklahoma, the Arkansas Valley in southeastern and the upper South Platte Valley in northeastern Colorado, the upper Missouri Valley through the Dakotas and Montana, the lower elevations of

FIG. 5. Average summer temperature (June-August) over the Great Plains and adjoining sections.

the eastern Black Hills in South Dakota, and the Yellowstone and Bighorn Valleys of Montana and Wyoming. Sections where spring arrives comparatively late and fall early, and where the growing seasons are relatively short, are found on the highlands of western Texas and eastern New Mexico, in northwestern Nebraska, and from eastern Wyoming north-northeastward to southwestern North Dakota.

Climatic Limitations to Agriculture.—In a general way, from the viewpoint of temperature, crops may be divided into two classes, cool climate crops and warm climate crops. Among the former may be included potatoes, wheat, oats, buckwheat, sugarbeets, flax, and most grasses; among the latter, cotton, corn, rice, sugarcane and peanuts. Thus, by suiting a given crop to favorable temperature environment, a wide climatic range in agricultural activity may be obtained. Owing to this fact, the temperature of the Great Plains is not a dominating factor in limiting their agricultural utilization, yet, even with adequate moisture and fertile soil, the rather well-defined latitudinal boundaries of the more eastern agricultural provinces would not be maintained in all cases. For example, the northern half of the cotton belt could not extend much farther west than at present because of the comparatively low summer temperatures and short growing season in northwest Texas and extreme eastern New Mexico. Cotton requires a mean summer temperature of at least 78° and a 200-day growing season for profitable production. At the same time, this section would fall thermally within the principal corn and wheat region which would extend westward to the foothills of the Rocky Mountains.

Farther north, in northwestern Oklahoma, the western portions of Kansas and Nebraska, and eastern Colorado, temperature conditions are favorable for more or less intensive cultivation of both corn and winter wheat, although it would be rather too cool for the growth of corn commercially in northwestern Nebraska and southeastern Wyoming. So far as temperature is concerned, the extension of the principal spring wheat belt through the western portions of the Dakotas into eastern Montana and northeastern Wyoming is favored, as well as the production of other cool climate crops. Winter temperatures ranging from 20° to 40° are favorable for winter wheat. Consequently the somewhat warmer winters in the interior of Montana would bring that section more into the winter wheat belt. Sugarbeets are grown most profitably at a mean summer temperature ranging from 68° to 72°. Temperature conditions favor this crop in much of South Dakota, northern and western Nebraska, and in the extreme western portion of the Plains region from Colorado southward, as well as in

the Yellowstone Valley of Montana. With adequate rainfall, most grasses would thrive throughout the region.

It has been shown that the seasonal distribution of precipitation in the Great Plains region is favorable for vegetative utilization of a large proportion of the amount received. At the same time the avail-

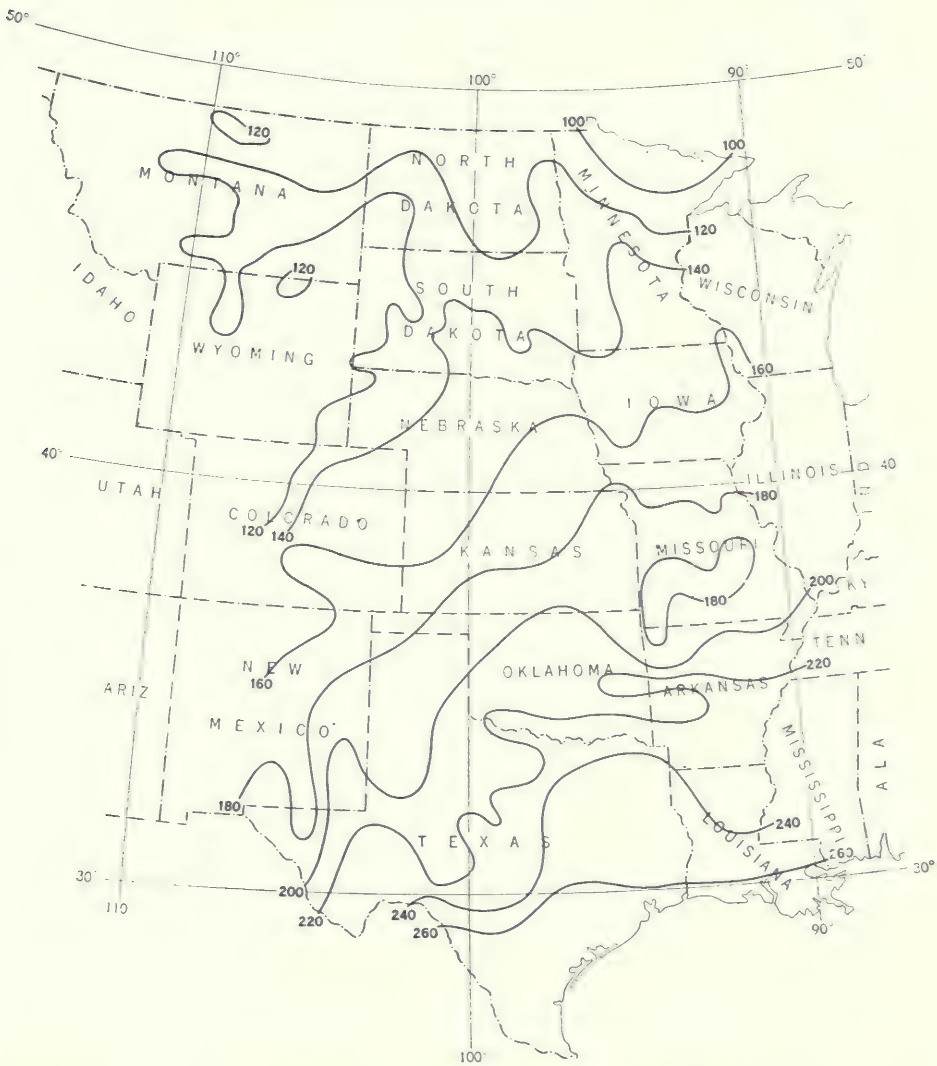

FIG. 6. Average length of the frost-free season over the Great Plains and adjoining sections. (Average number of days from the last killing frost in spring to the first in fall.)

able supply is scanty and summer evaporation, under the influence of comparatively large wind movement, high temperature, and low relative humidity, exacts a heavy moisture toll, particularly in the central and southern portions, while droughts are rather frequent. These inter-operating influences make the moisture problem exceedingly complex, but the final result is a rather frequently insufficient supply for profitable crop growth in a large portion of the region, particularly in the drier sections.

Farming, as ordinarily practiced, or even the so-called dry-farming methods, can never increase production of crops in the less favored localities sufficiently to be a material factor in the total food production of the country, although by careful tilth and fallowing, the more favored portions may contribute, in some measure, to the nation's supply. The drier portions of the region, considered from a climatic standpoint, are pre-eminently grazing areas, and must so remain until moisture is artificially supplied by irrigation.

At present only about one per cent of the Plains is under irrigation, but this can be materially increased and, at some future time, irrigation will doubtless be practiced extensively, where climatic conditions other than rainfall are favorable for intensive crop production. At present, where irrigation is practiced, the water is derived mostly from rivers, but a few sections at least, contain some underground water supplies and the comparatively high wind velocity suggests a cheap means of bringing this into service by harnessing the natural forces that are constantly expending themselves to no good purpose throughout the region. This is especially true for irrigating gardens or small truck plats to assure production of vegetables for family use, thus keeping cash outlay at a minimum.

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THE NATURAL VEGETATION OF THE GREAT PLAINS REGION

H. L. SHANTZ

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THE REGION HERE CONSIDERED.—The region considered in this paper (Fig. 1) lies between the Rocky Mountains on the west and the 97th degree of west longitude on the east. On the north it extends to the Canadian boundary and on the south to near the Mexican boundary. The line marking the eastern boundary of this region starts at the 98th degree of west longitude on the Canadian boundary and extends south along the western edge of the Red River valley. From a point west of Fargo, N. Dak. it leaves the Red River Valley and runs south and a little east until it reaches the 97th degree of west longitude in east central Nebraska. It then bends a little to the west and crosses the Oklahoma-Texas boundary at the 98th degree of west longitude. This line swings westward as far as the 99th degree of west longitude in Callahan and McCulloch counties, Texas, and then southeast, reaching the Gulf coast at about the 97th degree of west longitude. The western boundary follows the east side of the Rocky Mountains to the Montana-Wyoming boundary where it turns east to the eastern side of the Big Horn Mountains, extending south to the lower end of the Sangre de Cristo range where it turns west to the Manzano range, and east past the Sacramento, Guadalupe and Santiago mountains, thence east and later north to Fort Stockton, Texas. The western boundary line then runs north and west to the Texas-New Mexico line which it crosses about 50 miles west of the Pecos River. It then runs north to Roswell, New Mexico, where it swings across the Pecos, down the east side and crosses the New Mexico-

Texas state boundary 50 miles east of the Pecos River. The boundary line runs parallel to the Pecos at a distance of about 50 miles east of the river except for a short distance where it touches the Pecos River in Ward and Crane counties in Texas. It then runs parallel to the Rio Grande River for a distance of 50 miles northeast. The boundary line strikes the Rio Grande 60 miles above its mouth.

Correlation of Vegetation with Climatic and Soil Conditions.—Before discussing in detail the plant communities, it is necessary first to present a number of general considerations. The correlation between any single climatic or soil factor and the natural vegetation is often profoundly affected by change in the other factors. Similar distinct differences in the type of vegetation may be caused by any one of a number of factors. In correlating vegetation with conditions of soil or climate this consideration should be kept constantly in mind. When all other factors remain unchanged a close correlation can be made with the changes in any one factor of the environment. A change in either the rainfall, the soil texture, the soil depth, the available soil moisture, or the saturation deficit of the air, will be accompanied by a change in vegetation, if the other factors remain constant. If other factors vary, marked changes in one factor may produce no noticeable effect on the vegetation. The gradual decrease in the quantity of rainfall from east to west may be correlated with a gradual change in the natural vegetation. The greater quantity of rainfall in the south, as compared with the north, may produce no change in type of vegetation. This may be explained by the increase in evaporation and water requirement of the plants in the south as compared with those in the north. Differences in the depth of moist soil or in the available soil moisture may be closely correlated with changes in vegetation, provided the factors which control rate of loss of water do not vary in such a way as to equalize these conditions.

In dealing with plants we are equally concerned with the factors which determine the rate of loss of moisture from the plant and with the total available soil moisture supply. The quantity of rainfall is greater in the southern than in the northern portion of the Great Plains and a deeper layer of soil with moisture available for plant growth is produced. But this increase in moisture supply in the southern part is equalized by the higher water requirement. To produce a ton of dry matter, alfalfa required 518 tons of water at Williston, N. Dak., 630 tons at Newell, S. Dak., 853 tons at Akron, Colo., and 1005 tons at Dalhart, Tex.[1] Field studies of the rate of use of

[1]Briggs, L. J., Shantz, H. L. The water requirement of plants as influenced by environment. 2d Pan-American Scientific Congress, Wash., D. C., Dec. 27, 1915-Jan. 8, 1916. Govt. Printing Office, 1917.

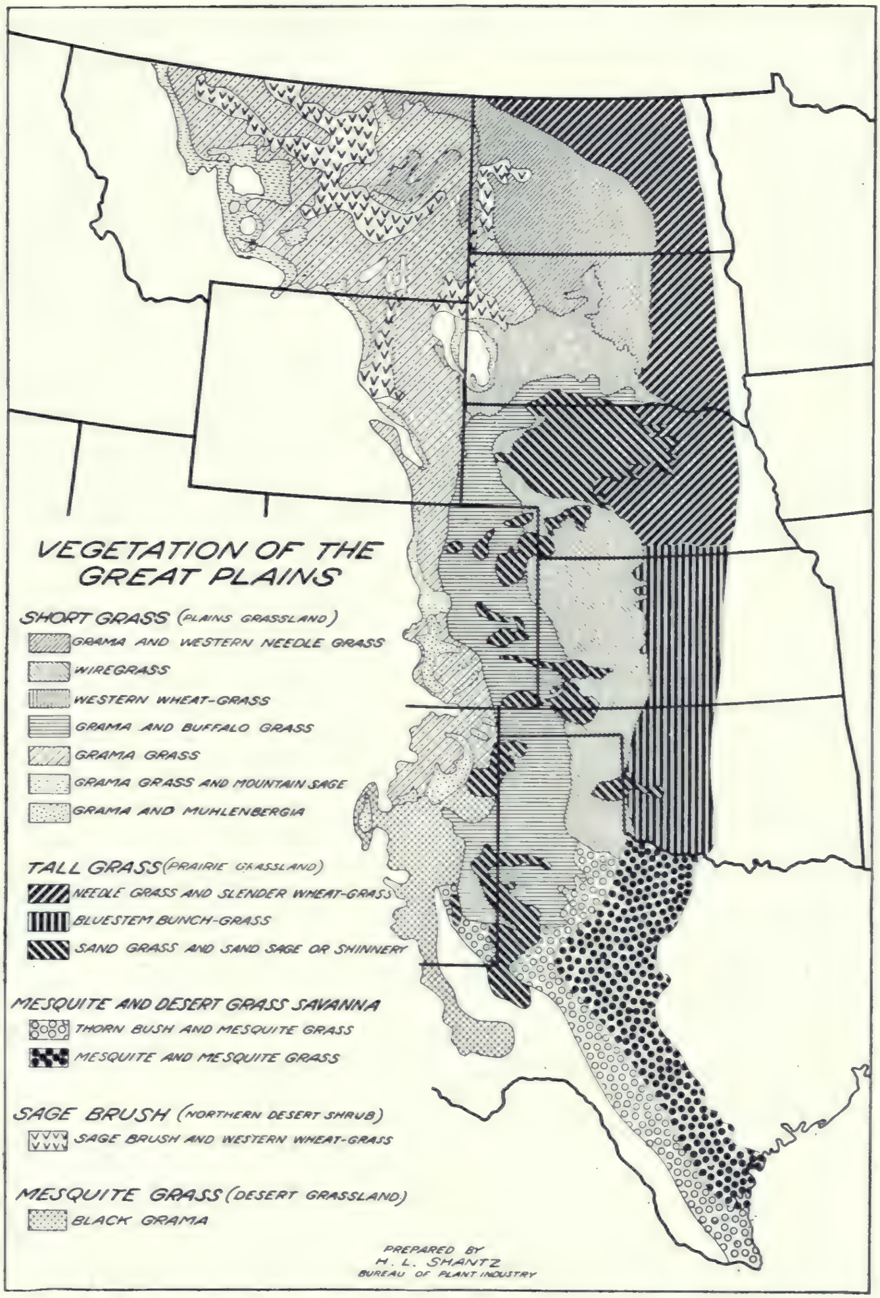

FIG. 1. Sketch map of the Great Plains region showing the areas occupied by the principal plant-communities.*

*In determining the boundary lines in the northwest the writer has been assisted by A. E. Aldous, Classifier, U. S. Geological Survey, and in the location of the sand-hill areas of the south, by C. F. Marbut, Scientist in charge of the U. S. Soil Survey.

water by a crop of spring wheat show the rate to be twice as great in the south as in the north.[2]

A factor of importance for plant growth is the length of the drought period. This is normally long in the south and short in the north. The rapid-growing grasses utilize the short growing period in increasing the vegetative part of the plant and producing seed. These grasses are drought-enduring and thus pass through the long drought-rest period without injury. The habitat factors measured throughout the year do not properly express the condition under which the vegetation develops. Evaporation, for example, is greater during the periods of extreme drought, when the water loss from the plant cover is almost negligible, because there is no water present for it to use. When plants are well supplied with moisture and rapidly transpiring the evaporation is likely to be relatively low. The evaporation measurement expresses potential loss of water. In any given area on the High Plains the evaporation measurement for different periods of the frost-free season is probably more nearly inversely correlated than directly correlated with the actual water loss from the area.

If soils of similar texture are considered, the depth of the layer of periodically moistened soil is an indirect measure of the amount of available soil moisture. Throughout this region the subsoil is permanently dry to a depth of many feet. When rain falls it moistens the surface soil. Not until this is filled to the moisture equivalent, or a little below this percentage, does moisture pass to the soil below. The soil moisture remains near the surface and does not pass down unless additional rains add to the total moisture supply. It is not drawn up to replace the moisture lost from the surface by evaporation. The surface dries but there is no appreciable upward or downward movement of the liquid. Plants rapidly absorb the soil moisture and pass it off into the air by transpiration if the moisture lies within reach of their active roots.

The soil profile, like the vegetation, is a summation of the climatic conditions over a long period of years. Variations in vegetation are not as nearly proportional to total rainfall as variations in soil profile. The increased demand of the plant for moisture in the warmer portions of the Plains, due at least in part to the increased saturation deficit of the warmer air, reduces the efficiency of the soil moisture if measured in terms of plant production. This effect does not operate on the moisture penetration in soils during heavy rains or during periods where the plants are not rapidly absorbing soil moisture.

[2]Cole, John S. and Mathews, O. R. Use of water by spring wheat on the Great Plains. U. S. Dept. Agriculture Bul., No. 1004, 1923.

The profile or depth of soil is not in itself the factor which determines the plant cover. Both the vegetation and the soil profile are determined largely by the same factors, chiefly the parent soil material and the climate.

Under the same climatic condition soil texture modifies the profile profoundly. The profile layers lie deeper in the lighter soils and nearer the surface in the heavy soils. The depth of these layers, especially the layer of carbonate accumulation, can be correlated with the plant cover through the medium of available soil moisture. When this difference in depth is due to variation in soil texture the effect on the plant is due both to the change in the water-holding capacity of each unit of soil and the quantity of total moisture available. A heavy soil will hold one inch of rainfall in the surface 6 or 8 inches. The surface moisture is lost rapidly by evaporation. The soil moisture is readily available to the roots and growth is rapid and luxuriant. The same amount of rainfall would penetrate to a foot or more in sand. Growth would be less rapid since not all of the moisture is available to the roots at the same time and they must be pushed far into the soil to reach the moisture supply. Moisture, within the quantity retained in dry-land soils, does not move to the roots through any considerable distance. The roots must therefore grow to the moisture supply. Consequently more time is consumed and drought delayed much longer in sand than in heavy land. This is true of the cultivated as well as the native crops.

Vegetation has an important reaction on soil profile. In eastern Colorado the layer of carbonate accumulation develops at 14 to 18 inches under a short-grass vegetation. Had there been no vegetation to absorb the soil moisture the layer of carbonate accumulation would never have developed. When the vegetation is destroyed by cultivation the depth of moisture penetration is greatly increased, even if the land is continuously cropped. Alternate cropping greatly increases the penetration of soil moisture[3] and crop plants normally grow in a soil which is moist below the layer of carbonate accumulation. Theoretically the layer of carbonate accumulation would be lowered under cultivation. The depth of soil to the layer of carbonate accumulation is a measure of the depth of moisture penetration under the natural vegetation during all but exceptional years. The soil profile affords,

[3]Even under conditions of cultivation moisture seldom penetrates below two or three feet and with alternate cropping only rarely is moisture stored to a depth of five or six feet. See Mathews, O. R., " Storage of Water in Soil and its Utilization by Spring Wheat. U. S. Dept. Agriculture, Bul. No. 1139, 1923.

therefore, an indirect measure of the moisture condition during normal years. Unless other factors interfere vegetation and soil profiles can be closely correlated. This correlation is not perfect and the failure to correlate exactly affords an important means of interpreting the habitat.

In drawing general lines of plant distribution it is important that only mature soils of comparable texture be considered. Along the line between the tall grasses and the short grasses if the soil becomes light in texture, sand in other words, the eastern or tall-grass types will push west. A bluestem bunch-grass cover characteristic of a good loam soil in eastern Kansas will entirely disappear from the loam soils farther west and be confined entirely to the sands, on which it extends into the deserts of New Mexico. Where very heavy land occurs in central Kansas it is likely to be characterized by the short grasses, this vegetation type being carried eastward by a heavy soil. The vegetation types are, therefore, carried far out of their natural climatic range by a soil of either heavy or light texture. Bluestem bunch-grass which occupies the well-developed loams with a depth of about three feet will push west on crests where erosion is taking place and where moisture penetrates several feet into the soil. This penetration is due largely to the open spacing of the plants and the reduction in the rate of use of soil moisture. Bluestem bunch-grass is carried west beyond its range by flood water or by a sandy soil, since moisture penetration is relatively deep in both cases. This type occurs even in the blowouts of the heavy clay where clay granules blow about as sand. It is also characteristic of the pure gypsum sand dunes of New Mexico and occurs on eroded areas of caliche in the southern Great Plains. It is, therefore, not the depth of the layer free of carbonate accumulation which determines the growth of this species in central Kansas, but rather the depth of moist soil which is indicated in the well-developed soils by the depth to the layer of carbonate accumulation. On new or eroded soils carbonates may occur at the surface and the moisture condition still be favorable for the grass. Passing eastward from the high plains this type is soon shut out except on sand dunes or sandy land. Here it is evident that sand offers perfect drainage and consequently the best conditions for a relatively xerophytic grass. In the humid east the drainage is perfect in sand dunes, and bluestem bunch-grass succeeds well on sand in Illinois and Indiana, and on the Hempstead Plains of Long Island.[4] Sand to some extent equalizes the habitat. In the arid country it furnishes

[4]Harper, Roland M. Some dynamic studies of Long Island vegetation. Plant World, v. 21, No. 2, 1918.

the most favorable moisture condition, and in the more humid country the perfect drainage affords a favorable habitat for the xerophytic grasses. In short, the widest distribution from humid to dry habitat occurs on sand. Clay will often carry western types, especially short grasses, some distance east. The line of demarcation between the short-grass and the tall-grass vegetation must be swung east on heavy soils, and west on sands.

In making a generalized map of the plant associations it is necessary to recognize clearly the successional stages initiated by overgrazing or breaking. Before the vegetation can be successfully correlated with agricultural potentialities, successional and climax stages must be clearly recognized. Undeveloped sand dunes or areas of very young soils are characterized by a successional stage of vegetation. The sand hills on the Great Plains are constantly tending toward the normal short-grass type of the region. The soil profile enables one to discern clearly old and new soils. Climax types of vegetation occur only on older soils, those soils which have come into equilibrium with the climatic conditions. The soil profile affords a valuable means by which to determine whether the vegetation is a climax or merely a successional stage.

There are then two methods of evaluating the habitat, namely, by the proper interpretation of the vegetation and by the proper interpretation of the soil profile. The soil profile as an aid to the study of vegetation is now made available to the botanists in this country through the work of the Bureau of Soils[5] and should greatly influence future study of vegetation.

From the considerations above it is clear that, in outlining on a generalized map, areas characterized by different types of vegetation, the occurrence of the type on mature soil, soil with a well-developed profile, should first be considered. These types of vegetation are climax types which have come into equilibrium with the soil and climatic conditions. Since a light soil or a heavy soil modifies the soil profile and the vegetation, it is well, if climatic climax vegetation areas are being outlined, to consider chiefly the vegetation which occurs on well-developed loam soils. Breaking destroys the vegetation and overgrazing often modifies it profoundly. It is therefore necessary to take these factors into consideration in deciding which type represents the original vegetation. These precautions are especially necessary in regions where most of the original vegetation has been destroyed. Failure to recognize the stages of succession would often lead to erroneous estimates of the importance of different communities.

[5]See Marbut, C. F., in this number of the Annals.

The Plant Communities.—The vegetation of the region here outlined is not uniform. Along the eastern edge in any portion north of the Canadian River the grasses are relatively tall and the area resembles a luxuriant meadow. Farther west the tall grasses disappear and the short grasses predominate. The short grasses resemble a well-grazed pasture. South of the Canadian River a scattered growth of trees over a relatively short-grass cover presents the appearance of an orchard of small fruit trees. In the southwest the grass cover may become sparse and the appearance is that of a desert grassland. In the northwest plants characteristic of the great desert push east on the poorer land and produce a vegetation consisting of scattered grasses and shrubs.

The region considered in this paper extends too far east and too far south to be regarded as a natural vegetational unit. It includes within its boundaries parts of the following plant formations and minor communities.

Short Grass (*Plains Grassland*).*—Grama grass (association), grama and buffalo grass (association), grama and western needle grass (association), wire-grass (association), western wheat-grass (association), grama grass and mountain sage (associes), grama and Muhlenbergia (associes).

Tall Grass (*Prairie Grassland*).[a]—Needle grass and slender wheat-grass (association), bluestem bunch-grass (association), sand grass and sand-sage (associes), shinnery (associes).

Mesquite and Desert-Grass Savanna (*Desert Savanna*).[b]—Mesquite and mesquite grass (association), thorn bush and mesquite grass (associes).

Sagebrush (*Northern Desert Shrub*).[c]—Sagebrush and western wheat-grass (associes).

Mesquite Grass (*Desert Grassland*).[d]—Black grama (association).

Four criteria may be used in separating the formations, namely: physiognomy or general appearance, floristic composition, develop-

*A small portion of this grassland which pushes across the highlands of N. Mex., Ariz. and into Utah, is not included.

[a] Here are included only the two western associations and two developmental phases (associes) which push west on sandhills.

[b] The greater part of this community is included here, but it does not cover extensive areas in the United States.

[c] Only a few outstanding developmental areas of this type are included. These have pushed from the deserts into the Great Plains in Montana and Wyoming.

[d] Only part of one association located at the eastern edge of the formation is here included.

ment of vegetation or succession within each area, and environmental conditions or the habitat.

Short Grass (*Plains Grassland*).—The typical appearance of this grassland as a whole is that of a closely pastured meadow. Except during years of more than normal rainfall the taller growing plants are almost entirely absent, and the vegetation presents the appearance of extreme monotony. There is little variation in appearance from north to south or east to west. Changes in the vegetation within the area are due largely to differences in soil texture, run-off or flood-water irrigation which affect the available soil moisture supply.

The transition to the tall-grass formation is gradual on the east where many of the taller plants occur. On the west many species characteristic of the foot-hill region enter and modify the pure short-grass cover which is characteristic of the central portion of the area.

In spring the short grasses start growth as soon as temperature conditions are favorable. Many flowering plants vary the monotony of the short-grass cover. If the season is unusually dry these plants are usually inconspicuous, and even the short grasses may fail to put up flower stalks. If the season is unusually moist annuals and herbaceous perennials often become a prominent component of the vegetation.

In botanical composition the area varies considerably and several associations may be recognized. By far the most important plant is grama grass (*Bouteloua gracilis*), which occurs throughout the extent of this formation. Buffalo grass (*Bulbilis dactyloides*) does not occur in the north and west portions of the area, but is much more important than any other species with the exception of grama grass. In the northeast western needle-grass (*Stipa comata*) and western wheat-grass (*Agropyron smithii*) are important, while in the east wire-grass (*Aristida longiseta*) often becomes a prominent feature. Along the western border nigger wool (*Carex filifolia*) and mountain sage (*Artemisia frigida*) are often important, and in the southwest matchweed (*Gutierrezia sarothrae*) becomes equally important. Among the plants not considered as dominating associations but very prominent in the vegetation are the perennials *Koeleria cristata, Sporobolus cryptandrus, Schedonnardus paniculatus, Psoralea tenuiflora, P. argophylla,* and the annuals *Festuca octoflora, Plantago purshii, Boebera papposa, Leptilon canadense, Helianthus annuus, Lappula occidentalis,* and *Hedeoma nana.* During favorable years gum weed (*Grindelia squarrosa*) becomes prominent, although this plant requires an unusual combination of two favorable seasons for its best development. In the southern portion it may grow as a perennial, the old stems putting out branches from the base during the third season.

The short grass formation is typical for the Great Plains. Along the Canadian boundary it occurs from western North Dakota across Montana to the Rocky Mountains. It extends in a broad band down across the Great Plains and almost to the southern escarpment of the High Plains in Texas. On the west its boundary is the same as that of the total region here considered (Fig. 1). On the east it follows rather closely the 2000-foot contour. In the north this boundary line starts between the 102d and the 103d degree west longitude and runs southeast just west of the Mouse River Valley and crosses the North Dakota and South Dakota boundary just east of the 99th degree of west longitude. From this point it runs south and a little west and strikes the Missouri River in the southern part of Brule county, South Dakota. The boundary then swings west around the great sand-hill area of Nebraska, then southeast and south across Kansas a little west of the 99th degree of west longitude, bending westward and extending south along the east boundary of the "Panhandle" of Texas. In Texas the short-grass formation is limited to the "Panhandle" and the southern portion of the High Plains. In eastern New Mexico it is also limited to the High Plains and to portions of northeastern New Mexico. Within this area there occur large tracts of sand hills dominated by tall grasses, and areas of poor soil and low rainfall in the northwest dominated by sagebrush and western wheat-grass.

Overgrazing or breaking destroys the plant cover and initiates a succession leading to the reestablishment of the original vegetation. This succession varies somewhat in different parts of the area. The following stages may be recognized: (1) an annual-weed stage consisting of *Boebera papposa, Plantago purshii, Salsola pestifer, Verbena bractiosa, Lappula occidentale* and *Hedeoma nana,* or similar plants; (2) a perennial stage consisting chiefly of mountain sage (*Artemisia frigida*) in the north, or matchweed (*Gutierrezia sarothrae*) in the south, or wire-grass (*Aristida longiseta*) in the east, all nearly valueless for grazing; (3) the short grass reestablished in a period of 30 to 60 years.

As a rule the vegetation starts growth when suitable temperatures occur in the spring. The frost-free period is short in the north (80 to 120 days) and long in Texas (210 days). Seasonal growth, although usually initiated by suitable temperature, is seldom terminated by low temperature.

The rainfall decreases from east to west and from south to north, ranging in the north in portions of Montana to 15 inches, while in the eastern portion in Nebraska, Kansas, Oklahoma, and Texas it ranges from 25 to 30 inches.

Over the whole of this area the layer of periodically moist soil is shallow. This is especially true in the northern and western portions where the layer of carbonate accumulation lies at a depth of from 8 to 18 inches. In the southern and eastern portions the soil may be two feet in depth. Beneath this there is a layer of carbonate accumulation and a dry subsoil. In the southern portion this layer of carbonate accumulation has developed into caliche, forming a rock-like layer beneath the surface soil. The moisture available for growth in this formation at the beginning of the growing season seldom exceeds that held in the first 1 or 2 feet of soil, or the equivalent of 2 or 3 inches of rainfall. The stored soil moisture and the rainfall of spring and early summer enable growth to continue until early in July. At that time practically all of the stored water and that added by the rains has been consumed. The plants then pass into a drought-rest condition which may be broken occasionally by summer or fall rains. During exceptionally wet years, growth may continue almost without interruption throughout the whole season. In extremely dry years, the period during which moisture is available in the soil may be so short that even the buffalo grass, which can flower within 30 days, is prevented from flowering. The dominant species of this formation are without exception drought-enduring plants. They are able to grow rapidly during periods when moisture is available and to pass into a dormant condition when drought occurs. They resume growth quickly when moisture is again supplied. The majority of the annuals can ripen seed during a very short season of growth and are able to produce a few seeds even during the drier years. In such years the plants are depauperate. During wet seasons these annuals may form an extensive portion of the vegetation cover.

Available moisture is about twice as great in the southeast as in the northwest. The evaporation for the six months from April to September, inclusive, from a water tank 2 feet deep and 6 feet across, buried to the soil level, varies from 33 inches in the north to 50 inches in the south.

The moisture requirement of the plants is about twice as great in the south as in the north, but, since the moisture supply is also greater, the moisture conditions for the growth of native plants are much the same.

In this formation we may recognize the following principal plant associations: Grama grass (association), grama and buffalo grass (association), grama and western needle grass (association), wire-grass (association), western wheat-grass (association), grama grass and mountain sage (associes), grama and Muhlenbergia (associes).

The grama-grass association dominates the northwest portion and extends in a rather narrow zone along the east face of the mountains. The grama and buffalo-grass association, characterizes the central and southern Great Plains, and extends from South Dakota across the plateau region of Texas. The grama and western-needle-grass association occupies the northeast portion and is most prominent in North Dakota and South Dakota. The wire-grass association extends across Nebraska, Kansas, Oklahoma, and the eastern portion of the "Panhandle" of Texas. The western-wheat-grass association is most extensively developed in the northern portion, especially in South Dakota on the Pierre shales, where it occurs over extensive areas. The grama-grass and mountain-sage associes, may be recognized skirting the mountains, dominated largely by grama grass with an admixture of nigger wool (*Carex filifolia*) and mountain sage (*Artemisia frigida*), and many other species which characterize the eastern foot-hills of the Rockies. This is not an extensive community and is more or less mixed because much of the area over which it is growing has not reached a stable condition. The soils have not yet developed their profile, and the whole area may be considered as indicating a slow and gradual successional change. In some of the drier valleys of Colorado and New Mexico grama grass is mixed with or gives place to Muhlenbergia to form the grama and Muhlenbergia associes.

Grama-grass association (Pl. IIIa)—The dominant plant in this association is grama grass (*Bouteloua gracilis*). With this there are also found in many places *Carex filifolia, C. stenophylla, Koeleria cristata,* and a wide range of herbaceous plants, such as *Artemisia frigida* and *Phlox hoodii,* in the north, and *Gutierrezia sarothrae* in the south. In general appearance it is typical short-grass land.

The area occupied by this association forms a wedge, very broad in the north and very narrow in the south, lying just east of the mountains. In Montana it extends from the mountains on the west to the eastern boundary of the state, but in Colorado forms only a narrow band.

This grassland occupies a soil which is very shallow, ranging in depth from 8 to 18 inches to the layer of carbonate accumulation, below which is a permanently dry subsoil. The soil moisture available during normal years is equivalent to from 1½ to 2½ inches in rainfall, the supply being replenished by occasional rains during the period of plant growth. The moisture supply is lowest in the north and increases somewhat to the southward. Rainfall ranges from 15 to 20 inches. The period free from killing frost is relatively short, from 80 to 150 days. The evaporation ranges from 33 inches in the north

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a. Grama grass association (short grass). *Bouteloua gracilis* with *Carex filiofolia* and an occasional plant of *Stipa comata*. Glendive, Montana, August 22, 1916.

b. Grama and buffalo grass association (short grass). A pure stand of *Bouteloua gracilis* and *Bulbilis dactyloides*. Sharon Springs, Colo., Oct. 5, 1922.

to 50 inches in the south. The growth period is generally terminated by drought. There is no storage of water from year to year, and only during years of exceptional rainfall does water penetrate the soil below the layer of carbonate accumulation. It is excellent grazing land with a carrying capacity of from 15 to 30 cattle per section. During years of more than normal rainfall, land characterized by this association produces excellent small-grain crops.

Grama and buffalo-grass association (Pl. IIIb.)—The grama and buffalo-grass association is typical of the High Plains. The plant cover is often uniform and covers the ground with an open or dense mat-like growth. During wet years the short grass flowers and many annuals and perennials become prominent in the plant cover. It is dominated by almost equal quantities of grama grass (*Bouteloua gracilis*) and buffalo grass (*Bulbilis dactyloides*). Often the cover is almost pure but at other times there are mixed with these grasses many small annuals (such as *Plantago purshii, Festuca octoflora, Hedeoma nana* and *Lappula occidentale*). During years of more than normal rainfall, other and more prominent plants, such as *Leptilon canadense, Grindelia squarrosa, Stipa comata,* and *Sporobolus cryptandrus,* are prominent.

This association extends from South Dakota across western Nebraska, eastern Colorado, southwestern Kansas, northeastern New Mexico, western Oklahoma, and northwestern Texas.

The rainfall over this area is somewhat higher than over the grama-grass area and ranges from 15 to 20 inches. Evaporation measurements vary from 35 to 55 inches. The soil is not as shallow as under grama grass, the depth to the layer of carbonate accumulation ranging from 14 to 18 inches. The soil moisture stored in the soil at the beginning of the growth season amounts to the equivalent of from 2 to 3 inches, except during abnormally dry or abnormally wet years. The water requirement of plants is relatively high in this association. Alfalfa to produce a ton of dry matter requires in this association in eastern Colorado about 800 tons of water, and in the same association in Texas from 1,000 to 1,400 tons of water. The frost-free period is from 120 to 210 days in duration. The period of growth, however, is often as short as from 30 to 60 days on account of drought. The better types of land where rainfall is supplemented to some extent by drainage water within this area are marked by the occurrence of plants characteristic of the wire-grass association. This condition occurs in many places where alluvial soil is collecting and the moist soil is deeper.

Soil moisture records for the native vegetation extending over a period of 9 years at Akron, Colo., show available moisture in the third

foot of soil only once during this period. During several years no available moisture was recorded in the second foot. A four-year record at Amarillo, Texas, indicates about the same conditions of soil moisture under the native sod.

This association furnishes excellent grazing land with a carrying capacity of from 20 to 40 head of cattle per section. Crop production is good during years of more than normal rainfall. In the north small grains do fairly well in medium or wet years, but fail in dry years. Sorghum and short-season corn are grown, and in the south a small quantity of cotton has been produced.

Grama and western-needle-grass association (Pl. IVa.)—The appearance of this association is much more varied than that of almost any other portion of the short-grass formation. Except during years of extreme drought the plant cover does not look like a mat of short grasses. The short grasses are important but are overtopped by taller grasses and herbaceous plants. The association is dominated by grama-grass (*Bouteloua gracilis*) mixed with western needle grass (*Stipa comata*). With these dominant grasses there occur other important grasses and many herbs such as *Psoralea argophylla* and *Eschinacea angustifolia*.

This association occupies the southwestern half of North Dakota. Isolated areas occur in Montana, and in the northern part of South Dakota occupying a relatively large area both east and west of the Missouri River.

This plant association is limited to an area receiving from 15 to 20 inches of rainfall. Over the area evaporation is relatively low, probably ranging from 30 to 35 inches. The soil is relatively dark with the layer of carbonate accumulation at from 18 to 24 inches below the surface. The moisture storage at the beginning of the growth season is nearly as high as in any other portion of the short-grass cover, being equivalent to 3 or 3½ inches of rainfall. The frost-free period is short, from 90 to 150 days. As a rule the growth of vegetation which begins with the approach of suitable temperature conditions in the spring is terminated in July or August by the complete exhaustion of the available moisture supply. Two factors combine to make the area occupied by this association the best of any in the short-grass formation for crop production: first, a rainfall sufficient to moisten the soil to a depth of 20 to 30 inches; second, a cool climate which keeps down the excessive loss of water by evaporation or transpiration. The water requirement of plants in this section is relatively low. Alfalfa requires 500 to 800 tons of water in this area to produce a ton of dry matter.

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a. Grama and western needle grass association (short grass). A good cover of *Bouteloua gracilis* and *Stipa comata*. Prominent plants are *Psoralea argophylla*, *Artemisia dracunculoides*, *Polygala alba*, *Artemisia frigida* and *Echinacea angustifolia*. Mandan, N. Dak., July 15, 1915.

b. Wire-grass association (short grass). A rather dense stand of *Aristida longiseta* with *Bulbilis dactyloides* and *Bouteloua gracilis* forming a sod cover underneath. Hays, Kan., June 29, 1918.

This association affords excellent grazing and has a carrying capacity of from 20 to 60 cattle per section. It characterizes the best wheat land in the short-grass formation, land which can be relied upon to produce good crops during all but the drier years.

Wire-grass association (Pl. IVb.)—In appearance the wire-grass association is more varied than the typical short-grass cover. The ground is covered by a mat of short grasses. Overtopping this mat the wire-grass and other taller plants may become so dense as to obscure the short grasses entirely.

The wire-grass association is an abbreviated name for what in full should be grama and buffalo and wire-grass association. Both grama grass(*Bouteloua gracilis*) and buffalo grass (*Bulbilis dactyloides*) are grasses of great importance in this area, but with these there occurs a relatively even stand of wire-grass (*Aristida longiseta*). This association is a more luxuriant eastern phase of the grama and buffalo-grass association.

This association lies between the grama and buffalo-grass association on the west and the bluestem-bunch-grass association of the tall-grass formation on the east. The most extensive areas are in southwest Nebraska, western Kansas, the eastern portion of the "Panhandle" of Texas, and the intermediate area in Oklahoma.

This plant association characterizes an area in the central portions of the Great Plains where the frost-free period ranges from 120 to 220 days. The soil is much deeper to the layer of carbonate accumulation than in the grama and buffalo-grass association. The soils are chestnut brown with the layer of carbonate accumulation at a depth of from 18 to 30 inches. Rainfall is approximately 18 to 22 inches and the evaporation from 40 to 55 inches. The quantity of water stored in the soil at the beginning of the growth season is greater over this area than over the grama and buffalo-grass area and may amount to the equivalent of from 2½ to 3½ inches of rainfall. Water is not stored from one season to the next and almost every year the entire available supply is exhausted during the month of July when the plants pass into a drought-rest condition.

As grazing land this is little better than grama and buffalo grass. Much of the land in this area is crop land. The principal crops are corn in the northern part, winter wheat in Kansas and Oklahoma, some barley in parts of Kansas, and grain sorghum farther south, especially in eastern Texas. This region is one in which crop production is unusually good during favorable years, but in which crop failures are the rule during years of less than normal rainfall. As compared with the grama-grass and western-needle-grass area of the north it has

a higher rainfall and deeper soil; but the warmer temperature, higher rate of evaporation, and greater water requirement of crops, more than equalize the situation, so that crops are grown here under more extreme conditions than they are in the northern area.

Western-wheat-grass association (Pl. Va.)—The western-wheat-grass association is not as varied in appearance as the grama and western-needle-grass association. During years of drought wheat-grass makes little or no growth and the whole area may appear to be dominated by short grasses. During normal years, or years of more than normal rainfall, wheat-grass develops to give the area the appearance of a thinly planted grain field with short grasses forming a mat-like cover over the surface of the ground.

This association, in its typical form, consists of a dense cover of grama grass (*Bouteloua gracilis*) and buffalo grass (*Bulbilis dactyloides*) through which there is evenly scattered a growth of western wheat-grass (*Agropyron smithii*). A complete designation of the area would be grama and buffalo and western-wheat-grass association. This association is limited largely to the Pierre clays of South Dakota. In these clays moisture penetrates slowly and carbonates accumulate at a depth of from 14 to 24 inches. The high water-retaining power of the clay is detrimental to the storage of water since it limits the penetration to the surface layer where it is rapidly absorbed by plant roots or evaporated into the air. Consequently conditions cannot be regarded as favorable for continued growth on these heavy soils as on adjacent loam lands. In certain sections where the soil becomes alkaline the wheat-grass may occur with little or none of the short-grass cover. Such areas should not be confused with the one under discussion, since the conditions are entirely different. They will be discussed under the sagebrush and western-wheat-grass associes. The rainfall over the wheat-grass area ranges for the most part from 15 to 20 inches. During years of heavy rainfall the quantity of moisture is sufficient not only to mature the short grass but also to enable the wheat-grass to make good growth and ripen seeds. Usually drought occurs in midsummer and the whole area passes into drought-rest condition in late summer and autumn. The growth period is therefore determined by water supply and not by temperature, for the frost-free period is long, ranging from 120 to 150 days. Evaporation in this area is relatively low, 35 to 40 inches. The soil is very rich and during years of more than normal rainfall will produce excellent crops of cereals. The heavy character of the soil is conducive during dry years to extreme conditions, during which crop production is precarious and the production of native forage greatly lessened. The water re-

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a. Western wheat-grass association (short grass). A good cover of *Bouteloua gracilis* and *Bulbilis dactyloides*, and a relatively good stand of western wheat-grass (*Agropyron smithii*). The hay cut from this type consists largely of western wheat-grass. Philip, So. Dak., July 21, 1908.

b. Grama and Muhlenbergia association (short grass). A practically pure stand of *Muhlenbergia gracillima*. Near Pueblo, Colo., Oct. 10, 1922.

quirement throughout this area is relatively higher than in the grama-grass or grama-stipa areas to the north and considerably lower than in the grama-buffalo or wire-grass areas to the south. It is excellent grazing land and will carry from 30 to 75 cattle per section.

Grama-grass and mountain-sage associes.—Along the mountain front grama grass (*Bouteloua gracilis*) is often mixed with a great variety of plants which are more typical of the mountain grasslands. Among these may be mentioned *Artemisia frigida, Carex filifolia, Achillea millefolium,* Eriogonums of various species, Pentstemons, wild roses, and lupines. These characterize an area in which the rainfall is greater than that of the adjacent grama-grass land. The soils are often not well developed but consist of loose granitic gravels. Where land is level and favorable for cultivation conditions are much better than in the grama-grass areas farther east. With this type may be thrown such outstanding areas as the Judith Basin where, on account of peculiar topography, the rainfall is sufficiently high to develop a good soil and make crop production relatively secure. Small grains are the chief crops grown in this area. As grazing land it will carry from 20 to 30 cattle per section.

Grama and Muhlenbergia associes (Pl. Vb.)—In the southeastern portion of the region considered in this paper, especially in Colorado and New Mexico, near the mountains, conditions become so extreme as to temperature and drought, that grama grass gives way to *Muhlenbergia gracillima.* With this often occurs the cane cactus (*Opuntia arborescens*). This associes characterizes land of inferior production, even as grazing land, and of doubtful value for crop production.

Tall Grass (*Prairie Grassland*).—The region here considered includes only the western portion of this great grassland. The formation as a whole characterizes the great prairie region of the Mississippi Valley. The area is dominated by tall, luxuriant and relatively deep-rooted[6] grasses. With these are associated a large variety of herbaceous flowering plants. During spring the prairie is a veritable flower garden, but grasses are dominant over the whole area.

The portion considered in this paper forms a broad belt from north to the south across the east side of the region. In the north it extends across almost the whole of the North Dakota boundary. The western boundary has been defined as the eastern boundary of the short-grass formation (see p. 89) and the eastern boundary as the eastern boundary of the region (see p 90). The sand dunes within the area characterized by short grasses are included in the tall-grass formation.

[6]Weaver, John E., Root Development in the Grassland Formation. Carnegie Institution of Washington, Publication No. 292, 151p., 23 pl., illus. 1920.

A Comparison of the Tall-Grass and Short-Grass Formation.—The great grassland which extends across the Mississippi Valley from the forests of the east to the foothills of the Rockies may conveniently be divided into the tall-grass formation or prairie grassland, and the short-grass formation or plains grassland.

The general character of growth habit of the dominant plants serves to differentiate these two areas. The typical form in the plains grassland is the grama grass, a low-growing plant which puts up comparatively weak and short flower stalks. Only a few scattered taller grasses occur in this formation. As a whole the area is characterized by the mats of short grasses between which are areas of bare soil. In the prairie grassland the grasses are tall with prominent flower stalks. They never produce the low mat-like cover characteristic of the plains grassland, but a sod or bunch-like growth. The prairie is a relatively tall wheat-grass or bluestem grassland, while the plain is a short buffalo and grama-grass or grama-grass land. In general appearance the vegetation of the plains resembles a closely pastured field, while that of the prairie resembles a relatively luxuriant meadow.

From the east to the west in the central region of the great prairies the composition of the plant cover shows a gradual change accompanied by a lessened moisture supply. *Andropogon furcatus, Sorghastrum nutans* and *Panicum virgatum* become less abundant at the eastern boundary of the region considered in this paper and bluestem bunch-grass becomes more dominant. Farther west bluestem bunch-grass gives way to buffalo grass and grama grass. In the north slender wheat-grass and needle grass give way to grama grass. Here the division line is drawn which separates the prairie grassland (tall grass) from the plains grassland (short grass). The causes of this difference in plant cover are differences in the habitat. The most important factors in bringing about this change in vegetation are the quantity of soil moisture supplied by the rainfall and the length of time during which soil moisture is available. The length of the growing season is determined almost entirely by the available moisture.

The development of the vegetation in the short-grass and the tall-grass formation is not the same. Disturbed areas or areas of new land, if located in the short-grass area, may at first be occupied by tall grasses, but are finally dominated by short grasses. Areas of short grass occurring on heavy land or on overgrazed land within the prairie area, if left undisturbed, develop into tall grass.

The boundary between the prairies and the plains as here defined does not coincide with a topographic boundary. No greater topographic change is encountered in crossing it than is encountered in

traveling a similar distance within either the prairies or the plains. The boundary line lies near the 2000 feet contour.

On the basis of soils (Fig. 2) the divisional line is much sharper, but here also the change is gradual. The division line between the short grass and tall grass corresponds to rather sharp soil differences and marks the western edge of the chernozem zone. The plant distribution is correlated with the depth below the surface of the layer of

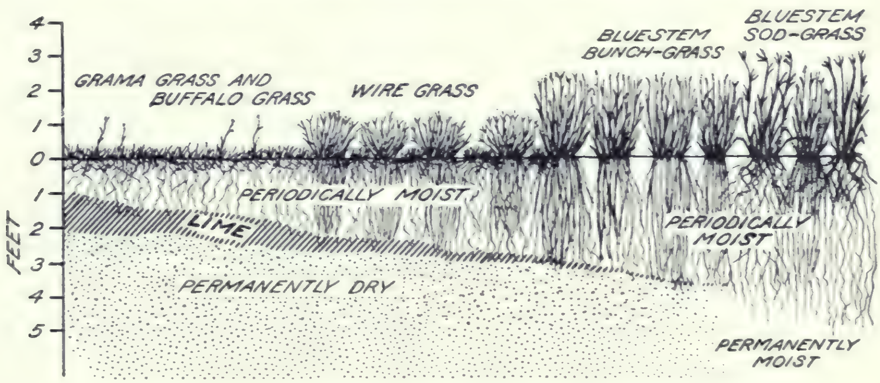

FIG. 2. A sketch showing the relation of the plant communities to the depth of penetration of soil moisture and to the layer of carbonate accumulation. The boundary between the short grass and the long grass formations is drawn where the wire grass is replaced by bunch grass.

carbonate accumulation. Where this depth is less than two feet, the plains type of vegetation predominates. Where greater than about 30 inches, or where lacking entirely, the prairie type of grassland occurs. The important point here is the depth of soil periodically moistened by rainfall and the total moisture supply available. Short grass characterizes areas where each season all available soil moisture is consumed by plant growth. All available soil moisture is also consumed along the western edge of the tall grass in the area considered in this paper. Over the tall-grass area as a whole, however, moisture during the rainy period penetrates so deep into the soil that it is not all recovered and brought to the surface by the plants. Consequently the carbonates are carried down and away entirely with the drainage water. At the beginning of the growth period the soil is moist to the layer of carbonate accumulation, the equivalent of from 4 to 6 inches of rainfall in the tall grass and from 2 to 4 inches in the short grass.

By far the sharpest soil boundary line, that of the disappearance of the layer of carbonate accumulation in the subsoil (Fig. 2), lies well within the area characterized as prairie grassland. This soil boundary

corresponds in a general way with the eastern boundary of the two tall-grass associations considered in this paper. Here the moisture penetrates below the reach of plant roots. Under these conditions there is no dry subsoil between the moist surface soil and the water table. The soil moisture supply is great enough to support a tree vegetation, but on account of the drought of the autumn and late summer, grass fires sweep the area and destroy the young trees as rapidly as they are produced. Farther west where the moisture penetration extends to a few feet only in depth, where the subsoil is permanently dry and there is a distinct accumulation of carbonates at a depth varying from 2 to 4 feet below the soil surface, the tall grasses still find sufficient moisture to maintain themselves. This is a true grassland, a prairie not dependent on fire probably for its maintenance. To the west as the depth of soil moisture becomes less than 2 feet and the tall grasses disappear because of insufficient moisture supply; this is due directly to decreased rainfall and indirectly to the competition of the short grasses. In general, the short grass grows on a shallow soil with a layer of carbonate accumulation at a depth of 1 to 2 feet. The vegetation boundary between the tall grass and the short grass formation is of great agricultural importance since it separates the highly productive farm lands of the prairie from the less productive ranch lands of the plains except where it swings west around sand hills.

Four divisions which occur within the area here considered may be recognized in the tall-grass cover:

Needle grass and slender wheat-grass (association)
Bluestem bunch-grass (association)
Sand-grass and sand-sage (associes)
Shinnery (associes)

Needle-grass and slender-wheel-grass association (Pl. VIa.)—The needle-grass and slender-wheat-grass association is characterized by grasses of moderate height and by many prairie herbs. The grasses do not turn red as do the Andropogons farther east and south. Their appearance is that of a relatively luxuriant meadow of grasses with slender flower stalks. The chief grasses are needle grass (*Stipa spartea*) and slender-wheat-grass (*Agropyron tenerum*).

This association occupies most of eastern Nebraska, South Dakota and northern and eastern North Dakota. Along the eastern boundary which lies near the 97th degree of west longitude this type is replaced by the tall Andropogons of the Andropogon sod association. On the south the bluestem-bunch-grass association replaces it just north of the Nebraska-Kansas boundary.

a. Needle grass and slender wheat-grass association (tall grass). A good stand of *Agropyron tenerum* and *Stipa spartea*. Edgley, No. Dak., Aug. 1918.

b. Bluestem bunch-grass association (tall grass). Typical close stand of bunch grass on sand land, far west of the typical range of this association. Southeast of Yuma, Colo., Sept. 12, 1908.

In this association the plants start growth early in the spring, as soon as temperature conditions are favorable, and continue usually until late in July, when droughts occur. This grassland characterizes a relatively heavy soil. The soil is black and 3 feet or more in depth to the layer of carbonate accumulation. During the early part of the growing season the soil may hold in storage as available moisture the equivalent of 5 inches of rainfall. The region as a whole has a relatively short frost-free period, ranging from 100 to 170 days. The growth period, even in this section, is usually terminated by drought, the total soil-moisture supply being consumed by the grass cover. There is consequently no storage of moisture in the soil and no drainage through the subsoil to the water table below. The evaporation in this region is relatively low. Few measurements have been made but the range is probably from about 30 to 40 inches. Rainfall ranges from 15 to 20 inches in the northern and from 20 to 30 inches in the southern part of the area. This type of vegetation characterizes land which has proved highly productive. On the basis of the value of all crops[7] this type of vegetation is designated by the areas of high production in eastern North Dakota, South Dakota, and Nebraska. The chief crop in the southern portion is corn, and in the northern portion spring wheat. Oats, barley, and rye are also important crops in the northern part of the area. It characterizes, more than any other type here considered, the region best suited to spring wheat. This association furnishes excellent grazing land of high carrying capacity.

Bluestem-bunch-grass association (Pl. VIb.)—This association is characterized by bluestem bunch-grass (*Andropogon scoparius*). Where the grass forms a dense stand the whole area has the appearance of a grain field. The color is very dark when looking toward the wind, but very light when looking with the wind. Often the bunches stand some distance apart and the interspaces are occupied by shorter grasses or herbaceous plants. In general appearance this grassland is vastly different from that of the needle grass and slender wheat grass. Early in summer the grasses take on a reddish-brown hue and remain in this condition throughout the early autumn and winter unless previously grazed or cut for hay. It occupies a broad belt extending south from southern Nebraska across central Kansas and western Oklahoma to the Canadian River. This region, although characterized by bunch grass, has many small areas where the soil, because of its heavy character or because of overgrazing, supports an almost pure short-grass cover.

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[7]Baker, O. E. Graphic summary of American agriculture. Yearbook, U. S. Dept. Agriculture, 31, p. 433, 1921.

The moisture conditions in this association are much the same as in the grama and western-needle-grass association. The soils, however, are lighter in color, being more brown or chocolate-brown. The layer of carbonate accumulation lies at from 2 to 4 feet in depth and there is consequently no loss of water into the subsoil drainage. The quantity of stored soil moisture is greater here than in any other association considered and may be the equivalent of from 5 to 7 inches of rainfall. Rainfall throughout the year ranges from 25 to 30 inches. The growth season as determined by the length of the frost-free period ranges from 160 to 230 days and is rarely terminated by unfavorable temperature. As a rule growth ceases early in July when this grassland passes into a drought rest condition. Evaporation in this section is high, ranging between 40 and 50 inches.

The whole region is highly productive. Corn is important as a crop only in the northern part. The central and southern portion is the great winter-wheat area of the United States. In the extreme southern portion a large quantity of cotton is grown. The value of all crops is high over the whole area. It is good grazing land of high carrying capacity.

Sand-grass and sand-sage associes.—In regions lying in the central and south-central parts of the Great Plains area where the rainfall is low and the evaporation high, but where the soil is very light in texture, there occurs an associes very similar to the bluestem-bunch-grass association. Sand-grass (*Calamovilfa longifolia*), sand-sage (*Artemisia filifolia*), bluestem bunch-grass (*Andropogon scoparius*), and a large number of other grasses such as *Panicum virgatum*, *Sorghastrum nutans*, *Andropogon furcatus*, *Boutelouas*, and *Aristidas* characterize the area.

This associes represents an early stage of vegetation on sand hills which will give way gradually to bluestem bunch-grass when the soil has become stable and somewhat heavier in texture. The conditions here are not as favorable for plant growth as in the bluestem bunch-grass land, the soil being light, sandy and poor in nutrient material. Since the soil is loose and sparsely covered by vegetation it allows deep penetration of the rain water, some of which is lost to the subsoil, as is shown by the permanent streams which flow from such areas. The vegetation on this sand land continues to grow long after the plants on the adjacent hard land have dried out. In the sand hills of Nebraska and Colorado much of this land has come under cultivation. Fairly good crops of corn and sorghum are produced. Occasionally on the heavier land wheat is grown, but as a rule the danger of soil blowing is too great. These areas are principally valuable

for the production of forage. During the early days before the adjacent hard lands were occupied by farmers it was customary to save the sand-hills grazing for periods of snow falls when it was impossible to graze the short-grass on the adjacent hard lands.

Shinnery associes.—Although not differentiated on the map, most of the areas mapped as sand-grass and sand-sage which occur in Texas, New Mexico, and Oklahoma are characterized by a low oak (shin oak—*Quercus havardii*) about 18 inches high. It does not branch to any extent and is usually mixed with bluestem bunch-grass which is of about equal height. The soil is a light sand entirely unsuited for crop production.

Mesquite and Desert-grass Savanna.—This plant formation does not belong to the High Plains. We pass here to a short-grass cover over which are scattered small trees or thorn bushes. Both the beginning and the end of the growth period are usually determined by available moisture. Temperature plays almost no part in limiting the growth of the natural vegetation. The distribution of water throughout the season is somewhat similar to that in the desert region. The rainfall is relatively heavy, but the high temperatures and the high saturation deficit of the air subject the plants to extreme drought conditions. There is a tendency over much of the area for the greatest rainfall to come in the spring and summer, during the period of greatest growth. Portions of the area have a rainfall of less than 20 inches, but in the eastern portion of the area it runs as high as 30 inches. Evaporation is high, from 45 to 70 inches.

This formation occurs in Texas south of the Canadian River and mostly south and east of the Plains border. It also extends over the lower southwest portion of the High Plains in Texas and southeastern New Mexico and also up the east side of the Pecos Valley.

Two divisions may be recognized within the area here considered:

Mesquite and mesquite-grass association;

Thorn bush and mesquite-grass associes.

In the eastern portion of this formation where the rainfall is relatively heavy, the trees large, and the grass cover rather dense, this type may be distinguished as the mesquite and mesquite-grass association. In the western portion of this formation the mesquite trees are small and there are many other small thorny trees and bushes which occur at intervals over an open grass cover. Much of the land is rough and broken and the vegetation partly in a developmental stage. This area may be designated the thorn-bush and mesquite-grass associes.

Mesquite and mesquite-grass association (Pl. VIIa.)—The mesquite and mesquite-grass association is one of the most distinctive types of

Texas vegetation. The trees may be either scattered or close together to form an open forest. They often give the appearance of an orchard of small fruit trees. Mesquite (*Prosopis juliflora*) is the dominant tree, although others occur. In many places, especially in the south and east, prickly pear (*Opuntia lindheimeri*) is almost as plentiful as mesquite. Grasses are abundant, chiefly curly mesquite (*Hilaria belangeri*), buffalo grass (*Bulbilis dactyloides*), and species of Aristida and Bouteloua. Mesquite is often damaged by drought.

In general appearance this association suggests an abundant water supply, followed by extreme drought. The soil is not deep, being only 1½ to 2 feet to the layer of carbonate accumulation. Although the rainfall is relatively heavy, 20 to 30 inches, it does not penetrate deeply into the soil and is rapidly absorbed and transpired by the growing plants.

This association forms a band about 200 miles wide extending from the Gulf of Mexico in the south to the Canadian River in the north. This band in the central portion is bent westward to Martin County, Texas.

The larger mesquite trees and much denser grass cover distinguish this association from the thorn-bush and mesquite-grass association. This is because the available moisture is greater in the mesquite and mesquite-grass area. On the north mesquite is apparently limited by low temperatures and on the east by the oak forests. Mesquite here grows on a dark soil with a layer of lime accumulation at about 2 feet. The oaks grow on sandier land of lighter color when the zone of carbonate accumulation has disappeared.

This area is suitable for grazing and the mesquite trees furnish both fence posts and fire wood. Much of this land has been put under cultivation. Cotton is the principal crop, although grain sorghums are important, especially in the north.

Thorn-bush and mesquite-grass associes (Pl. VIIb.)—In the thorn-bush and mesquite-grass associes mesquite and other thorn bushes and cacti are scattered over a sparse desert-grass cover. The soil is always visible because of the sparse vegetation.

The cover in this association is composed of curly mesquite (*Hilaria belangeri*), buffalo grass (*Bulbilis dactyloides*), species of Aristida, and other desert grasses. Mesquite trees (*Prosopis juliflora*) are scattered over this grass cover and with these are associated thorn bushes and cacti of various types.

This associes extends in a narrow strip from the Gulf of Mexico at the mouth of the Rio Grande River northwest to the southeast corner of New Mexico and across and up the southwest border of the High

a. Mesquite and mesquite grass association (mesquite and desert grass savanna). A good cover of *Hilaria belangeri*, *Bulbilis dactyloides* and a scattered growth of *Prosopis juliflora*. Haskel, Texas., Sept. 19, 1922.

b. Thorn brush and mesquite grass (mesquite and desert grass savanna). A scattered growth of mesquite and cat's claw and desert grasses on rough and broken land, east of Hagermann, New Mex., Nov. 30, 1920.

Plains. It also extends along the southeast border of the High Plains into Cottle and Motley counties, Texas. On the western edge this type passes either into southern desert shrub, in which case the grasses disappear and a shrubby, open growth takes its place, or into desert grassland, in which case the trees and shrubs disappear, leaving the grasses dominant.

The high water requirement in this hot climate and the long drought period make this type of doubtful agricultural value. Attempts have been made to grow cotton and grain sorghums in the better portions.

Sagebrush (Northern Desert Shrub).—The true sagebrush desert is not represented in the area here considered. There are, however, intrusions of the desert type on some of the poorer land of the northwest. These areas are largely the result of poor or alkali soils and more extreme climatic conditions. The most extensive areas occur on the heavy clay soils of Montana and Wyoming.

Sagebrush and western-wheat-grass associes (Pl. VIIIa.)—Where the short grasses drop out and the wheat-grass remains or is mixed with sagebrush, the soil is a heavy impermeable clay. There is alkali present in places but such areas are usually free from sagebrush which is replaced by saltbush. No continuous grass cover is formed on the breaks and clay flats. Such land is inferior to adjacent short-grass land for grazing land and is non-productive under cultivation.

Mesquite Grass (Desert Grassland).—Much of the area occupied by this formation lies outside of the region now being considered. Only a portion of the mesquite-grass formation occurring in eastern New Mexico and the eastern part of the Trans-Pecos region in Texas is included.

Black grama association (Pl. VIIIb.)—Black grama (*Bouteloua eriopoda*) characterizes the dry desert plains of west Texas and New Mexico. It does not form a sod but rather an open grass cover. Black grama is seldom an unmixed grassland, and there are often yucca, mesquite, and other desert shrubs scattered over the grass cover. The soil is shallow, often with carbonates at the surface. Rainfall usually starts growth during the summer when the temperature is high and evaporation rapid. Land of this character is valuable for grazing but is entirely unsuited to crop production without irrigation.

Brief Generalization.—In the area here considered the supply of rainfall is not sufficient to moisten the soil below the reach of the grass roots. No moisture is lost to the subsoil, and there is normally no storage of soil moisture from year to year. The subsoil is permanently dry. Over much of the area the soil is filled to its carrying

capacity only to a depth of 1 to 4 feet below the surface. This soil moisture is absorbed and passed out into the air by transpiration before the first frosts in autumn. The growth period is therefore initiated by favorable temperature but terminated by drought.

The total quantity of water stored at the beginning of the season is equivalent to from 2 to 5 inches of rainfall. To this initial supply must be added the rainfall during the growing season. This may vary from 2 to 15 inches.

The moisture supply is greater in the south than in the north, but the water requirement of the plants is proportionately greater. For the growing plant the moisture conditions are therefore similar.

The needle-grass and slender-wheat-grass area is one of rich, deep, black soil moistened to a depth of 2 to 3½ feet at the beginning of the growth period. The water requirement of plants is lower than in any other area of the region considered. The area produces a good stand of relatively tall grasses valuable for forage and native hay. The land, under cultivation, has become the great spring-wheat area of the United States.

South of the needle-grass and slender-wheat-grass area the bluestem-bunch-grass association characterizes a soil moist from 2 to 4 feet. A good growth of tall grass is produced, valuable both for pasturage and native hay. This association characterizes the great winter-wheat area of the United States. This area is also productive of corn and alfalfa.

South of the bluestem-bunch-grass area, the mesquite and mesquite-grass area is one of alternating severe drought and good moisture supply. The area is not as favorable for plant growth as those just mentioned. Cotton is produced throughout the area and grain sorghums are grown chiefly in the north.

The groups of plant associations just considered represent land primarily valuable for crop production. Lying just west of this group of plant associations are the grama and western-needle-grass, the wire-grass, and the western-wheat-grass associations. Here crop failures are more likely to occur and agriculture rests both on crop production and grazing. Still farther west crops can only be produced during exceptionally good years, and the land is chiefly valuable for grazing.

On the basis of agricultural potentiality of the land the plant communities may be arranged as follows:

Land primarily valuable for crop production:

1. Needle grass and slender wheat-grass (spring wheat and other spring cereals)
2. Bluestem bunch-grass (winter wheat, corn, and alfalfa)
3. Mesquite and mesquite grass (cotton and grain sorghums)

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a. Sage brush and western wheat-grass association (sagebrush). Wheat-grass alone or wheat-grass associated with sagebrush or other desert shrubs often occurs on land which is too poor to support grama grass. Thirty miles northeast of Roy, Mont., Sept. 22, 1917.

b. Black grama association (mesquite grass). Mostly *Bouteloua eripoda*, Aristidas and annual grasses. West of Roswell, New Mex., Dec. 4, 1917.

Land valuable for crop production and grazing: (crop failures during years of less than normal rainfall):

4. Grama and western-needle-grass (spring wheat and other spring grains)
5. Wire-grass (winter wheat, corn, and grain sorghums in the south)
6. Wheat-grass (spring grains and corn)
7. Grama and mountain sage (spring grains)

Land valuable for grazing and crop production: good crops only during years of more than normal rainfall):

8. Grama and buffalo-grass (grain sorghums, corn, and small grains)
9. Mesquite grass and thorn bush (cotton and grain sorghums during good years only)
10. Sand sage and sand grass (corn and sorghum except in the southwest)
11. Grama grass (spring grains during good years only)

Land valuable for grazing only:

12. Sagebrush and western wheat-grass
13. Black grama

Numbers 1, 2, 4 and 10 are best as hay land. As grazing land the numbers would run about as follows: 1, 2, 6, 4, 5, 10, 7, 8, 3, 11, 9, 13, 12.

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THE AGRICULTURE OF THE GREAT PLAINS REGION

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CONTENTS

INTRODUCTION.—The Great Plains is the term commonly used by the residents of the region, as well as by geographers, for that broad belt of land having more or less deficient rainfall, grass covered and largely of smooth to undulating surface, which slopes gradually eastward from the Rocky Mountains to the central portion of the continent where humid conditions of climate prevail. The climatic conditions, especially the supply of moisture, determine primarily the systems of agriculture and cause the Great Plains to be classified as a distinct agricultural region—not the topographic conditions as the term "Great Plains" would indicate. Indeed, large areas in the Great Plains contain much rough land, especially in the northern section where many of the rivers are now running several hundred to a thousand feet or more below the original level of the plain, descent to the rivers being usually by a series of broad steps, each bounded by a band of so-called "breaks," or "badlands." In the central plains of eastern Colorado and western Kansas, erosion is much less advanced and the term "plains" is quite appropriate; but in the southern plains, especially along the eastern margin of the Staked Plains and in west central Texas, much of the land is rough and broken. The Staked Plains, however, constitute probably the largest area of almost level land in the United States.

PRESENT AGRICULTURAL SITUATION.—This Great Plains region is the last frontier of agriculture in North America. Settlement is still in progress, and systems of farming adapted to the varying geographic conditions are not yet fully established. It is this economic aspect of the situation in the region, especially the problem of land utilization, that is here presented.

In the semi-arid portions of the northern Great Plains during the last few years banks have been failing; many farmers have gone bankrupt, or have left the country and their land without that legal formality; property values have depreciated, sometimes from as much as $30 an acre down to $5 or less. Partial depopulation has occurred locally; even a few county governments have defaulted payment on their bonds, and one of the states was compelled for a short time to pay its officials with promissory notes. In 1918-1919 the President allotted 5 million dollars from the War Emergency Fund for seed loans in this region largely, and in 1921 and 1922 Congress appropriated 2 millions and 1½ millions respectively for this purpose.

The central and southern parts of the Great Plains are at present in a fairly prosperous condition, but in years past these areas also have experienced periods of successive dry seasons, with economic consequences similar to those now occurring in the northern plains. The

central plains are better able now to endure years of adversity than the northern plains because they have been longer settled and the farmers have accumulated more capital.

This serious situation in the northern plains area is due only in part to the unprecedented drought of three years' duration (1917-1919). Other important factors are the price of grain during the past three years, which has been lower than the cost of production, and the inexperience of many of the settlers. A recent survey of the former occupations of settlers in a county in Montana showed that only half had previously been farmers and that 30 per cent arrived with no capital. The list includes musicians, butchers, bartenders, miners and deep sea divers, maiden ladies and merchants, preachers, plasterers, printers and peddlers, gamblers and jacks-of-all-trades. Of those with previous farming experience only 52 per cent have abandoned their farms, while 70 per cent of those without previous experience have left for other fields of work. Of those with capital 58 per cent have failed to stay, while of those with no capital 70 per cent have left.*

Perhaps of as great importance as the unsuitability of some of the settlers to pioneer farm life is the unsuitability of the systems of farming adopted by many in their ignorance of the geographic conditions, or because of their poverty. The selection of an unsuitable system of farming, moreover, often has been forced upon the settlers by the small size of the homestead permitted by law. Sixteen hundred acres in much of this region produces no more than 160 acres in the Eastern states. Fundamentally the situation is attributable in large measure to delay in the adoption of a national land policy suited to semi-arid climates. The settlers have had to make the best of an arbitrary law. This has usually involved the sale of land by one settler to an adjacent settler or rancher, and the consolidation of the holdings into a unit sufficient in size to support a family. Often this has meant blasted hopes and sometimes the waste of several years of the homesteader's life.

The serious situation in the Northern Great Plains has led the United States Department of Agriculture, in cooperation with the state agricultural colleges and experiment stations, to endeavor to determine with more or less precision the geographic conditions in the different portions of the Great Plains region and the systems of farming and size of farms which are necessary to support a family in

* This information was supplied by Mr. M. L. Wilson, of the Montana Agricultural College, who recently completed a study of the causes of success and failure of farmers in Hill County.

accordance with the American standard of living.* Many of the successful settlers in the region are recent immigrants who have survived the adverse seasons largely because of their low standards of living. But their children are not likely to be satisfied with less than the American standard, and if the agriculture of the region is to be permanent and satisfactory, it should afford nothing less than a comfortable living for the farmer and his family.

Boundaries and Division Lines.—The eastern boundary of the Great Plains is determined primarily by the amount of precipitation (rain, snow, and hail) and is indefinite. By some geographers it has been based directly on the amount of annual precipitation, with due reference to increasing evaporation with increasing temperature toward the south; by others it has been determined according to native vegetation, which changes both in composition and quantity with changes in rainfall; still others have seized upon slight breaks in the topography or physiographic structure in drawing the boundary lines; while a few geographers, but more particularly popular writers, have been content to place the eastern boundary at the 100th meridian. The boundary of an agricultural region should be drawn on the basis of its agriculture, but as the settlement of most of the Great Plains is recent and the agriculture is immature, it seems best at present to determine the eastern boundary on the basis of the color of the soil and depth to the layer of lime accumulation, as well as upon farm practices and systems of farming, which tend to vary with the climatic and soil conditions.

The color of the soil in this region is dependent principally upon the character and luxuriance of the native vegetation, which in turn is dependent largely upon the amount of precipitation in relation to the evaporation. The depth to the layer of lime accumulation in the soil (shown by a lighter color and by effervescence upon application of acid) is likewise dependent primarily upon the precipitation, which leaches out a portion of the lime and other salts from the surface soil and carries these alkalies down to the depth, apparently, of its normal penetration. The color of the soil in places of normal development (where not subject to erosion, deposition, poor drainage, etc.), and the depth to the layer of lime accumulation are permanent and readily recognizable. These indicators of the possibilities of agricultural utilization do not vary in quantity from year to year like the precipitation; nor in quality and luxuriance like the native vegetation; but

*A series of bulletins describing the physical conditions and agricultural situation in the Northern Great Plains is in preparation by the U. S. Department of Agriculture cooperating with the agricultural colleges in the states concerned.

FIG. 1.—Climatic Belts of Great Plains Region.

represent the results of hundreds of years of development under the existing conditions, and, apparently, afford the simplest and safest criteria yet known of the adaptation of a district to the different systems of agriculture.*

The eastern boundary of this Great Plains region may be drawn (1) where the transition from humid to arid conditions first becomes noticeable in the soil and in the systems of farming, or (2) some distance west where the soil changes from black to dark brown in color and the acreage in pasture exceeds the acreage in crops, or (3) still further west where the soils become medium brown in color and the deficiency in moisture is so discouraging to crop production that farmers are compelled to place their principal dependence upon pasture and live stock, that is, where the value of the pasturage exceeds the value of the crops.

In this paper the zone where the influence of decreasing precipitation first becomes evident in the soil and in the sytsems of farming will be considered the eastern boundary of the Great Plains, in order that all of these moisture belts may be included in the discussion. But it should be noted that the second moisture line, i. e., where the acreage of pasture exceeds the acreage of crops, is of much greater significance agriculturally; and that the third line, where the value of the pasture exceeds the value of the crops, might be preferred as a boundary if one wished to restrict the Great Plains region to those areas in which pastoral systems of farming are dominant. Accepting the first line mentioned as the eastern boundary of the region for our present purpose, the second and third lines become significant interior division lines (Fig. 1).

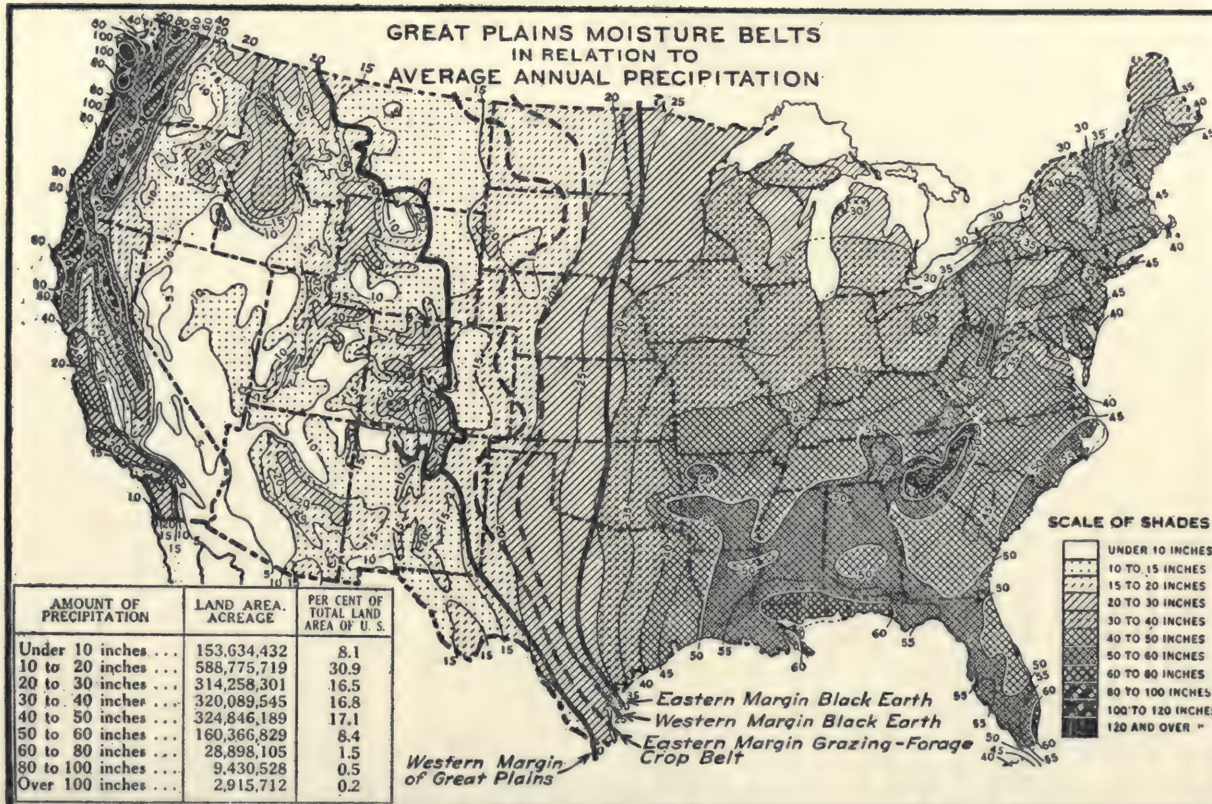
The Eastern Boundary of the Black-Earth Belt.—The eastern boundary of the Great Plains region is drawn where the layer of lime accumulation first becomes noticeable in the sub-soil of level, well drained, silty or clayey soils, usually at a depth of four to five feet, the rainfall being insufficient, apparently, to percolate entirely through the soil and carry away the lime and other salts in solution. The color of the soil also usually changes with the appearance of this layer of lime accumulation, the dark brown that characterizes the humid prairies developing into a positive black color. Along this zone timothy and clover give place to wild hay and alfalfa, the carrying capacity of the pasture decreases, corn, in general, begins to be less important and wheat more important, and listing becomes a common practice in the Central

* These soil criteria of agricultural utilization have been described more fully by Dr. C. F. Marbut, the vegetation criteria by Dr. H. L. Shantz, and the climatic criteria by Mr. J. B. Kincer in the June (1923) issue of the ANNALS.

Plains, particularly in Kansas and Oklahoma. The farms begin to increase in area, and, where other conditions are equal, a larger proportion of the land is in pasture.

This boundary line, or, to be more accurate, transition zone, follows along the eastern margin of the Red River Valley in Minnesota, passing near Thief River Falls, Detroit, and Fergus Falls, and, continuing southward and somewhat westward, crosses the state line into South Dakota, passing near Brookings and Yankton. The boundary then trends almost directly south across Nebraska, passing a few miles east of Norfolk and about 30 miles west of Lincoln. Near the Kansas line the boundary again veers slightly west and then continues straight south through Concordia and McPherson, Kan., Enid and El Reno, Okla., whence it veers a little westerly to Henrietta and Brownwood, Tex., then slightly easterly, and, passing near San Antonio, reaches the Gulf of Mexico at Corpus Christi (Fig. 1). The average annual precipitation along this easternmost boundary of the Great Plains increases from 22 inches in northwestern Minnesota to 29 inches in Nebraska and 30 inches in Oklahoma and Texas (Fig. 2).

The Western Boundary of the Black-Earth Belt.—From 125 to 175 miles west of this easternmost boundary of the Great Plains, except in North Dakota where the distance along the Canadian boundary increases to 320 miles, we come to the second line, which is one of the most distinct agricultural boundaries in the United States. This zone of rapid transition, where pasture acreage becomes greater than crop acreage and humid systems of farming give way to semi-arid systems, practically coincides with the change in color of soil from black on the eastern side in the Dakotas, Nebraska, and Kansas, or reddish black in Oklahoma and Texas, to a dark brown to the west. The layer of lime accumulation is found usually at 20 to 24 inches. The change in the productivity of the land, size of farms, and systems of farming along this line is, in general, abrupt. The value of farm land along almost the entire length of this line was close to twenty-five dollars an acre in 1919, and the average value of farm products in that year was about ten dollars per acre, except in North Dakota, where the drought reduced it to about seven dollars (Fig. 16). Fifty miles east the value of the farm products in most counties was over fifteen dollars per acre, fifty miles west it was under five dollars. Fifty miles east of this line the average size of farms is 300 to 400 acres, fifty miles west the farms average, in general, from 600 to 1200 acres. Fifty miles east of this line, indeed usually up to this line, the landscape looks like an agricultural picture in the humid prairie region. The land is practically all in fields and most of the fields are in crops.



AMOUNT OF PRECIPITATION	LAND AREA. ACREAGE	PER CENT OF TOTAL LAND AREA OF U. S.
Under 10 inches . . .	153,634,432	8.1
10 to 20 inches . . .	588,775,719	30.9
20 to 30 inches . . .	314,258,301	16.5
30 to 40 inches . . .	320,089,545	16.8
40 to 50 inches . . .	324,846,189	17.1
50 to 60 inches . . .	160,366,829	8.4
60 to 80 inches . . .	28,898,105	1.5
80 to 100 inches . . .	9,430,528	0.5
Over 100 inches . . .	2,915,712	0.2

FIG. 2.—Moisture Belts and Precipitation.

Fifty miles west of this line the landscape in general looks like the plains. The fences usually are far apart, often lacking altogether, except along the roads, and more than half of the land is still covered with the native grass and used for pasture.

This line divides the United States into two parts almost equal in area. To the east is the region of humid climate farming, based upon tilled crops, small grains, and tame hay and pasture, though in eastern North and South Dakota and in Minnesota much wild hay also is cut. To the west is the region of dry-farming, grazing, and irrigation farming. East of this line the natural vegetation is composed largely of the andropogons and other tall or prairie grasses; west of this line, except on sandy soils, the dominant vegetation is grama, buffalo grass, and other short or plains grasses. For native vegetation as well as for cultivated crops this seems to be a critical line beyond which humid climate plants grow well only under unusually favorable conditions.

This line crosses the Canadian boundary near Portal, No. Dak., and trends southeasterly along the outer edge of the glacial moraines that cap the Missouri Coteau to within a few miles of Carrington, No. Dak., where it turns southward on the 99th meridian, passing through Leola, Faulkton and Miller to Gann Valley, So. Dak. Thence the line turns southwestward, crosses the Missouri River and passes a little to the west of Burke, So. Dak., then swings sharply southeasterly to O'Neill, Nebr., then southerly and westerly around the Sand Hills to North Platte, Nebr. From North Platte the line turns south again, first bending a little west to Atwood, Kan., then a little east, passing near Hoxie, Gove, Dighton and Cimarron. From Cimarron the line trends southwesterly through Liberal, Kan., to Amarillo, Tex., on the Staked Plains. South of Amarillo the line is again deflected toward the east, passing near Floydada, Snyder, and San Angelo. Crossing the Edwards Plateau, whose soils are mostly too shallow to possess a normal color or reveal a profile, the line reappears about 20 miles west of San Antonio, and, passing through Alice, reaches the Gulf of Mexico southeast of Kingsville (Fig. 1). The average annual precipitation along this line increases from 16 inches in northwestern North Dakota to 19 inches in east central South Dakota, 21 inches in southern Nebraska, and also in the Texas Panhandle, and 25 inches in southern Texas (Fig. 2).

The Western Boundary of the Farming-Grazing Belt.—From 50 to 150 miles west of this second line we come to the third line, which is drawn through those localities where the product of the pasture becomes of greater value than the crops; in other words, where cattle and sheep

ranching become the dominant systems of farming. This line is characterized along most of its length by a change in color of the soil from a dark brown to a medium brown, and the layer of lime accumulation rises to within 16 to 18 inches of the surface. The line crosses from Canada into the United States near Opheim, in northeastern Montana, and, after passing a few miles south of Scobey and Plentywood, Mont., turns south near Williston, No. Dak., and runs along the east side of the Little Missouri "breaks" about to Amidon, whence it trends southeasterly to the Missouri River at the South Dakota line, and follows the river to Pierre.* At Pierre the line turns southwesterly passing near Kadoka, So. Dak., and Chadron, Alliance, and Sidney, Nebr. From near Sidney the line swings southeast almost to Julesburg, Colo., then circles through Akron and Cheyenne Wells, Colo., to Tribune and Garden City, Kan. Thence the line turns southwesterly again to Elkhart, Kan., and Clayton, N. Mex., then southeast to Dalhart and Tascosa, Tex., and then southwest to include Curry County, N. Mex. The boundary then turns southeasterly through Portales, N. Mex., Brownfield and Big Spring, Tex., and after crossing the stony Edwards Plateau, passes about 10 miles east of Uvalde and Hebbronville and reaches the Gulf of Mexico near Brownsville.

The average annual precipitation along this line increases from 15 inches in northeastern Montana to 17 inches in central South Dakota and western Nebraska, 18 inches in eastern Colorado, eastern New Mexico and west central Texas, and 25 inches in extreme southern Texas, where the rainfall is more irregular and often torrential.

The Boundaries of the Arid, Sandy, or "Badlands" Grazing Areas. —Other boundaries deserving notice are those delimiting the driest areas where practically no crops are grown without irrigation, except a little corn, kafir or sorghum, and sweet clover for forage, usually on land which receives flood water from higher lands or possesses other favorable conditions. This almost purely pastoral agriculture is found also on lands of rough topography, or on very sandy soils, which preclude cultivation. These districts of arid climate, rough surface, or sandy soil do not form a continuous belt, but include in the aggregate a large area.

In Montana these grazing lands are found in the warm, dry valleys of the Yellowstone, Missouri, Musselshell, and Marias rivers, where the average annual precipitation is below 14 inches, and include also much of the valley of the Milk River. In North Dakota the badlands

* The Golden Valley lying along the Montana-North Dakota boundary on the western side of the Little Missouri Badlands possesses climatic conditions similar to those east of this line.

of the Little Missouri river is the only large area given over exclusively to grazing. In South Dakota these grazing lands include the badlands along the Cheyenne and White rivers, most of Harding and Butte counties, and those portions of Perkins and Meade where the average annual precipitation is less than 15 inches. Most of northeastern Wyoming belongs to this grazing type of land. In Nebraska the Sand Hills constitute the principal area, but parts of Sioux and Dawes Counties should also be included. In Colorado much of the unirrigated land in the South Platte and most of that in the Arkansas valley are suitable only for grazing, as is also most of the southeastern portion of the state in which the average annual precipitation is less than 16 inches. In Kansas only the Arkansas Valley west of Hartland and the sand hills to the south are included, and in eastern New Mexico, the Pecos Valley and drier portions of the upper Canadian Valley. In Texas practically all the area west of Midland, Sonora, Carrizo Springs and Hebbronville is suitable only for grazing, except where irrigated. In the Rio Grande Valley 20 inches of average annual precipitation is the minimum required for profitable crop production (Figs. 1 and 2).

The Western Boundary of the Great Plains.—The western boundary of the Great Plains follows along the foothills of the Rocky Mountains a distance of nearly 2,000 miles from the Peace River Valley of northern Alberta to the Pecos Valley of Southeastern New Mexico, where, because of the desert conditions existing in this valley, it crosses to the eastern side of the valley and continues southeasterly to about Odessa, Tex. South of Odessa it again approaches the Pecos River and continues southeasterly at a distance of 10 to 25 miles east of the Pecos river and Rio Grande nearly to Hidalgo, where the line crosses into Mexico and probably reaches the Gulf of Mexico about 75 miles south of Brownsville. The Great Plains Region, in other words, is bounded on the west for about 2,000 miles by the Rocky Mountain front (except for the gap in Wyoming between the Big Horn and the Laramie ranges), but for 500 miles along its southern extension it is bounded by the southwestern desert, and the boundary, accordingly, is less definite.

Area of the Great Plains Region.—As thus defined the Great Plains, including the sub-humid Black-earth belt, is a region about 2,400 miles long by 800 wide at its greatest breadth (along the United States-Canadian line) and contains an area of about 600 million acres, of which approximately 175 million acres are in Canada, 420 millions in the United States, and 5 millions in Mexico. In its southern extremity in Mexico, which is subtropical and almost frostless, palms

and citrus fruits are grown; while in its northern extremity in Canada only the hardiest crops can be raised, because of the frosts that are likely to occur any time in the summer. Along its eastern margin the climate is humid, while in southern New Mexico and Texas it is bounded on the west by the desert. Topographically it is one of the most uniform regions in North America, but climatically it is one of the most diverse. Owing, however, to the relatively uniform topography the climate changes, in general, are gradual and often almost imperceptible.

THE MOISTURE BELTS.—The three lines just described, that lie between the eastern and western boundaries of the Great Plains, divide the region into four moisture belts or areas,—(1) a sub-humid, black-earth crop farming belt, (2) a semi-arid farming-grazing belt, in which crops are dominant from the standpoint of value, (3) a more arid grazing-forage crop belt, in which grazing is more important than crop production, and (4) a series of disconnected arid, sandy or rough areas, which unirrigated are suitable only for grazing and the growth of drought resistant forage crops on favorable sites (Figs. 1 and 3).

The Black-Earth Belt.—Largest in area and most important agriculturally is the sub-humid, black-earth, crop-farming belt. This is the first transition zone between the humid East and the arid West. It is one of the most productive agricultural areas in North America. The normally high fertility of the unleached soil just about balances the defect of frequently deficient rainfall. The use of land for crops is limited primarily by topography rather than by climate. Farms average in size about one-third of a section of land (200 acres) along the eastern edge of the belt, and about a section (640 acres) along the western boundary, the average for the entire belt being 325 acres. The area of this Black-Earth belt in the United States is about 144 million acres, and it contained in 1919 about 380,000 farms.

The agricultural conditions in this belt are admirably summarized by Mr. John Cole, Bureau of Plant Industry, in a memorandum to the writer as follows: "In this belt agriculture is established and proven by a history of more than a generation. While more subject to drought, the production of important crops is not far below that of the more humid section. The limited supply of water, however, operates against the increase of production through intensive methods and specialization. This is the area in which grain farming on an extensive scale has been profitable. Rotation and practices to increase or maintain production per acre are primary problems here. Modification of the grain farming system by the introduction of other crops carries with it the introduction of live stock to consume them, and so

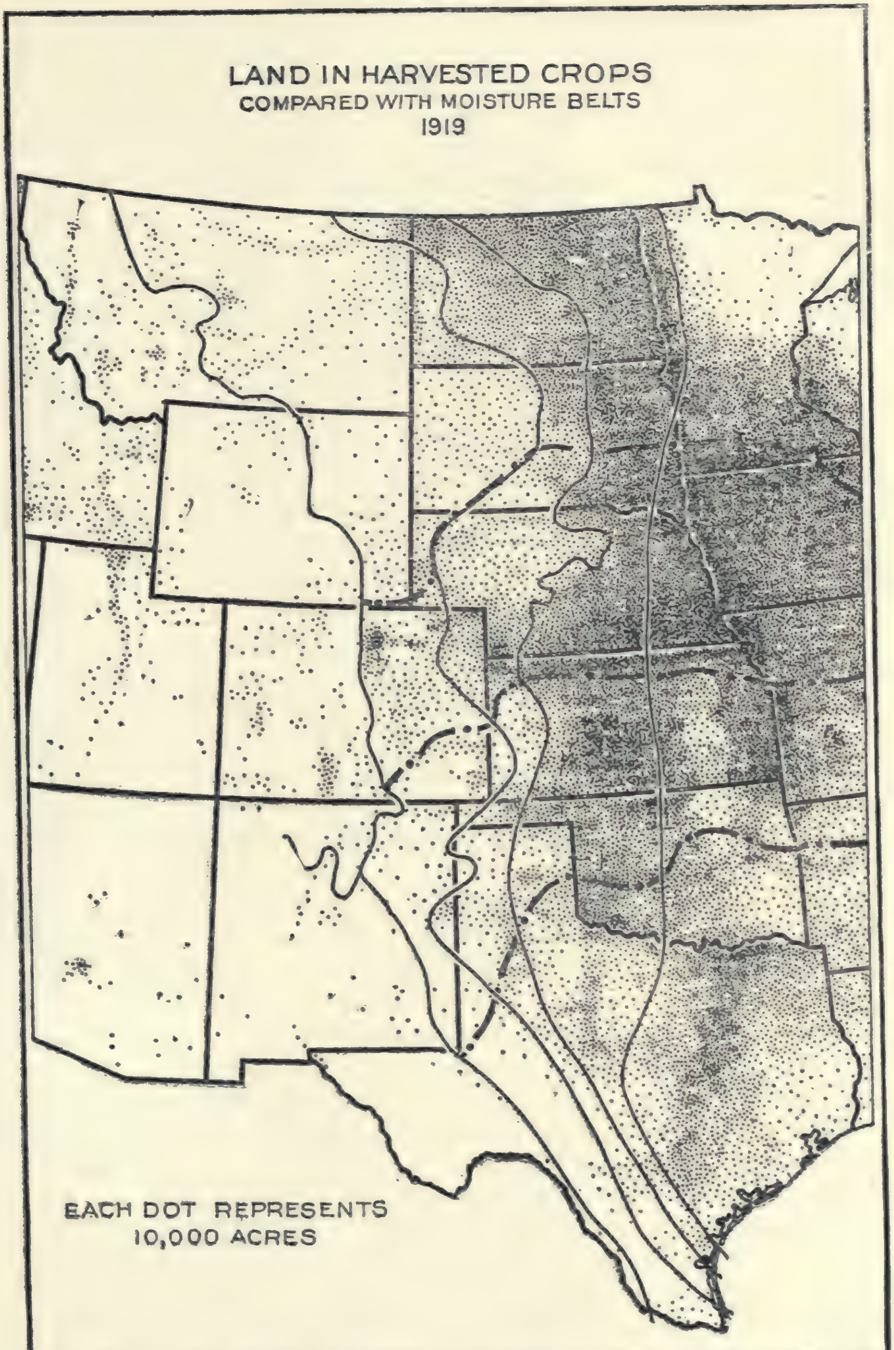


FIG. 3.—Distribution of Harvested Crops.

results in diversification as well as increased yields of the primary crops."

The Farming-Grazing Belt.—The second belt, which adjoins the Black-Earth belt on the west, and includes also the Judith Basin in Montana and certain moister benches on outwash plains beneath the Rocky Mountains, is the semi-arid Farming-Grazing belt. It is characterized by very dark to dark brown soils, with the layer of lime accumulation at a depth of one to two feet, and has a short grass vegetation, except on sandy soils. In this belt crop production, though uncertain, is more important than live stock production, except in dry years, when the live stock must provide most of the livelihood. One to two sections of land (640-1280 acres) are needed normally to yield a comfortable living. The average size of farms in the belt is only 683 acres, but much land not in farms is used for grazing, and if this were included the average size of farms would be about 900 acres. The area of this belt is about 81 million acres, and it contained in 1919 about 90,000 farms.

Mr. Cole summarizes the agricultural situation in this belt as follows: "Production is determined by the quantity of water available. The certainty of crop production is reduced more than the average yield in comparison with the more humid sections. Agricultural development has so far been determined by the uncertainty, by periodic production, more than by average production. The lack of available water operates entirely against increasing production by intensive methods. The necessity of reducing cost of production through extensive methods is indicated. Stabilization through the use of live stock to insure the continuance of the agricultural unit as a going concern through the poor years, in order that the returns of the good years may be realized, is an indicated necessity. Corn, wheat, native sod, bromegrass, and alfalfa, with live stock, is the dominant farm type indicated."

The Grazing-forage Crop Belt.—The third belt is the still drier, semi-arid Grazing-forage crop belt. The soils are typically brown to dark brown and the vegetation is largely grama grass mixed with nigger wool (*Carex filifolia*) in the north, buffalo grass in the central portion, and mesquite grass in the south. Wheat grass grows on heavy soils, especially in the north, and the tall grasses are often present on sandy soils. Crop production is precarious and the frequency of failure sufficient to reduce the average acre-yields to about three-fourths of those in the Farming-Grazing belt and to three-fifths those in the sub-humid Black-Earth belt. Crop production, however, can probably be carried on with profit in favorable sites, particularly if

extensive methods of cultivation are used and per acre cost is kept low. As Mr. Cole has noted,—"The primary object of cultivation in this belt is to produce feed-stuff, with an addition to the income from the uncertain but sometimes heavy crop of wheat produced at relatively small expense as a part of the rotation." Two to four sections of land (1280 to 2500 acres) are usually needed to make a family size farm. The area of the belt is about 120 million acres, and it contained in 1919 about 98,000 farms, excluding those in irrigated districts. This is only about 1225 acres per farm, but few of the farms in this belt, especially those recently started, are large enough to support a family in accordance with the American standard of living. Practically the only crops grown, other than wild hay, are wheat and corn or the grain sorghums for forage, except in southern Texas, where a little cotton is being raised. The corn is largely replaced by the sorghums in the Arkansas Valley and southward. Less than four per cent of the land was in harvested crops in 1919.

The Arid, Sandy and "Badlands" Grazing Areas.— Lastly to be noted are the arid, sandy, or "badlands" grazing areas. The soils in the arid areas are brown to ashy gray in color, and in the more arid portions the lime layer is near or at the surface. In such places the surface soil will effervesce upon application of acid. In these drier portions, which usually occupy the warm river valleys beneath the general level of the surrounding plains, crop production is normally impossible, except by irrigation. As already noted, rough lands, sand hills, "breaks," and "badlands" are included in these grazing lands, even where the rainfall is sufficient for crop production.

The drier lands in these arid areas are better suited usually to sheep than to cattle and 5,000 to 10,000 acres will often be required to support a fair sized outfit. On the "benches" and in the less arid portions about 25 acres in the northern plains to 50 acres in the southern plains will carry a cow or steer in a system of year-long grazing, and the number of acres required per farm may be only 2,500 to 5,000. The aggregate area of these arid and badlands grazing areas is about 70 million acres. Most of the irrigated land in the Great Plains region is found in these arid areas.

Temperature Divisions of the Moisture Belts.—These north-south trending moisture belts, more particularly the two eastern belts in which crops are more important than live stock, require division into sections, owing to their wide range in temperature conditions (Fig. 1). The most helpful division from an agricultural standpoint is that based on the dominant crops. But within the temperature zone suitable for cotton production the topographic peculiarities of this very diversified section must also be recognized.

The Spring Wheat Section.—The northern plains are characterized by the dominance of spring wheat. This section, which is the largest in area and importance among these temperature cross-zones, extends from the spruce and aspen forests of northern Saskatchewan and Alberta southward to central South Dakota, northwestern Nebraska and southwestern Wyoming. South and east corn becomes the dominant crop. Nearly all the flax in the United States and Canada is grown in this region, as is also much of the rye and barley. Wild hay is a very important crop.

The Corn Section.—The central plains require sub-division into northern and southern sections. The northern section is characterized by the dominance of corn, and extends from central South Dakota and west central Nebraska southwestward to eastern Colorado. It includes the northern tier of counties in Kansas. Winter wheat is a very important crop in this section also, but is not dominant except in three counties in south-central Nebraska, which are surrounded by corn-dominant counties. Winter wheat exceeds both spring wheat and corn in acreage also in a tier of counties along the northwest margin of this corn area in western Nebraska and north central Colorado.

The Winter Wheat Section.—The southern section of the central plains and the northern and western portions of the Staked Plains of Texas are characterized by the dominance of winter wheat, corn, and the grain sorghums. In the northeastern and eastern part of this winter wheat section the corn acreage exceeds that of the sorghums, but to the south and west the sorghums become more important, and in some counties even exceed wheat in acreage. This winter wheat, sorghum, and corn section of the Great Plains includes all of western Kansas, except the northern tier of counties, the Arkansas Valley of Colorado, all of New Mexico included within the Great Plains, the western and northern portion of the Texas Panhandle, and all of Oklahoma north and west of El Reno. To the south and east of this section cotton is the dominant crop.

The Cotton Section.—The cotton-growing section of the Great Plains requires subdivision into six districts on the basis primarily of topography and the relative importance of crops compared with pasture. The six districts include portions, respectively, of the Staked Plains, the Red Prairies and Breaks, the West Cross Timbers, the Grand Prairie, the Edwards Plateau, and the Gulf Coastal Plain (Fig. 4).

The Staked Plains district includes only that portion of the Staked Plains in which cotton is the dominant crop. The other important crops are the sorghums, corn, and wheat. The Breaks to the east have

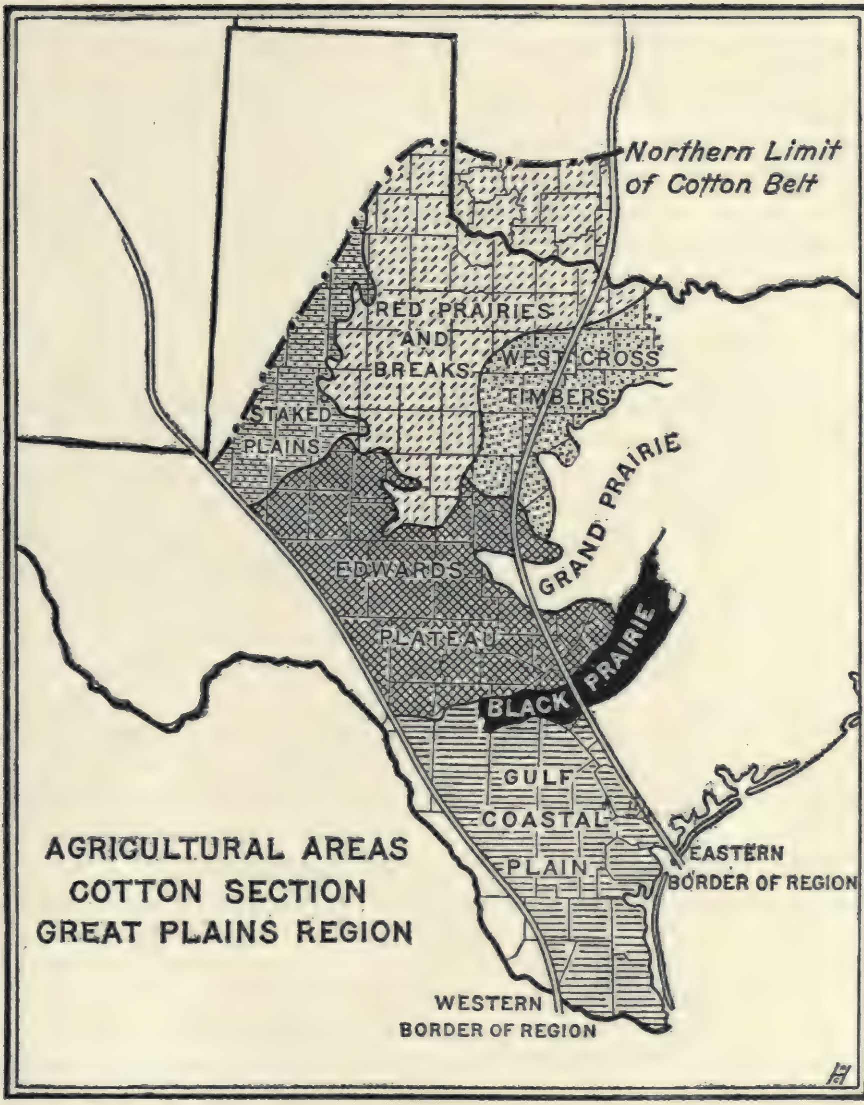


Fig. 4.—Agricultural Areas of Cotton Section.

little tillable land, and are used mostly for pasture. On sufficiently level areas of sandy soil the sorghums, corn, and a little cotton are grown, and on the harder soils occasionally a field of wheat also is seen. The Red Prairies, which include southwestern Oklahoma and much of north central Texas, contain some fairly good land, on which wheat, cotton, corn, and the sorghums principally are grown. The West

Cross Timbers include a large proportion of rough stony land, mostly covered with a scrubby oak forest. On the smoother and more fertile lands cotton, corn, wheat, and the sorghums are grown. The Grand Prairie projects only its western tip into the Black-Earth Belt, and has been made to include the granitic soils of Mason County.

A little south of Big Spring, San Angelo and Brady, Tex., the land rises, by low steps or escarpments, and becomes the Edwards Plateau. This is a limestone country with soil so thin in its central portion that not 10 per cent could be cropped even where the rainfall permitted. But it is a beautiful park-like country of short grass pastures with intermingled clumps of live-oak or mesquite, and a few junipers on the steepest slopes. The mesquite grass forms a sod beneath as well as between the trees, and upon this vegetation cattle, sheep, and goats are grazed. The cattle eat the grass, the sheep keep down the weeds, and the goats browse the brush and restrain the forest from intruding further upon the grassland. In the eastern moister portion of the Edwards Plateau the oak and mesquite become denser, forming a scrubby forest, while in the western portion the trees are scattered, dwarf, and finally disappear. In the eastern part of the Plateau a little wheat is raised by the German farmers in the narrow valleys between the limestone ridges. During the winter the wheat is pastured by sheep.

The Edwards Plateau slopes down more or less abruptly on the south, at the latitude of San Antonio and Del Rio, into the Gulf Coastal Plain, an area characterized by black lands along the coast, red semi-arid lands further inland, and ashy gray to yellow desert lands along the Rio Grande. Cotton, kafir, and corn are grown on farms sparsely scattered among the mesquite and thorn-bush dwarf forest westwardly to within 30 miles of the Rio Grande. Palms are planted for ornament throughout the area, and in the irrigated district along the lower Rio Grande many citrus orchards have been set out.

Crop Land in the Temperature Sections.—In the spring wheat and corn sections of the Black-Earth belt two-thirds of the farm area is in crops, a higher proportion than in the Corn Belt proper; in the winter wheat section, about one-half of the farm land is in crops; and in the cotton section less than one-third of the farm land (Fig. 3). In the spring wheat section there are 200 acres in crops per farm, in the corn and winter wheat sections 160 and 170 acres respectively, and in the cotton section 100 acres.

Similarly in the spring wheat section of the Farming-grazing belt, about one-third of the farm area is in crops (as compared with two-thirds in the Black-Earth belt to the east); in the section where corn

is the leading crop, which includes the Nebraska Sand-hills where almost no crops are grown, 29 per cent of the farm land is in crops; in the winter wheat and grain sorghum section, which includes much of extreme western Kansas and the western portion of the Texas Panhandle, 22 per cent of the farm land is in crops, and in the Cotton section 8 per cent. In the spring wheat and corn sections of this belt there are about 230 acres of crops per farm, in the winter wheat section about 140 acres, and in the cotton section about 85 acres.

THE CROPS OF THE GREAT PLAINS.—The principal crops in the Great Plains region are wheat, oats, barley, rye, corn, the sorghums, hay, and cotton. Sugar beets are also an important crop in the irrigated districts. Table I shows for the belts and temperature divisions the total acreage of harvested crops in 1919, the acres and value of all crops per square mile, the per cent of crop land in each important crop, the yield per acre, and the per cent the value of each important crop was of the value of all crops. It will be noted that the average acres of crops harvested in 1919 per square mile of land area (640 acres) decreased from 280 acres in the Black-Earth belt to 122 acres in the Farming-grazing belt, 40 acres in the Grazing-forage Crop belt, and 26 acres in the Arid and Badlands areas, which contain much irrigated land. The value of the crops per square mile likewise decreased from about $7,400 in the Black-Earth belt to $2,100 in the Farming-grazing belt, $850 in the Grazing-forage Crop belt, and $690 in the Arid and Badlands areas. If irrigated crops were excluded in these arid areas, the value of the crops per square mile would be about $200 (Figs. 1 and 3.)

Wheat.—The leading crop in the Black-Earth belt is wheat (Fig. 5). This is true also of the black-earth belts in Russia and in Argentina. About one-third of the wheat acreage and production in the United States and about one-tenth of the wheat acreage in the world are in this Black-Earth belt. In the winter wheat section of the belt, wheat contributed 60 per cent of the acreage of all crops in 1919. In the spring wheat section, wheat contributed about 44 per cent of the acreage of all crops, and receipts from the sale of wheat constituted from one-fourth to three-fourths of the farmers' income, varying with locality. In the Black-Earth belt as a whole, wheat constituted about 40 per cent of the acreage of all crops harvested in 1919; in the Farming-grazing belt, about 31 per cent; in the Grazing-forage crop belt, about 27 per cent; and in the arid areas, 26 per cent, of which a considerable proportion was irrigated. The acreage of wheat in the Black-Earth belt has decreased notably since 1919 and it constitutes now probably no greater proportion of the crop land than in the semi-arid belts and arid areas to the west.

TABLE

GREAT PLAINS

ACRES AND VALUE OF THE CROPS PER SQUARE MILE, RELATIVE

	Acreage of all Crops	Acres Per Sq. Mile	Value Per Sq. Mile	Wheat Percentage of		Wheat Yield Per. Acre Bushels	Oats Percentage of		Oats Yield Per. Acre Bushels
				Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops	
Great Plains Total........	86,967,504	138	3314	37.0	34.1	10.0	7.5	5.7	23.5
Black-Earth Belt..........	58,959,391	280	7389	40.6	36.4	10.7	9.1	6.6	24.8
Spring Wheat Section...	20,725,152	378	7238	44.1	43.7	8.0	13.0	9.8	18.5
Corn Section...........	14,832,655	362	9454	27.3	26.4	11.7	9.9	8.5	29.7
Winter Wheat Section..	15,193,557	264	6470	59.9	62.6	11.9	4.1	3.9	29.6
Cotton Section.........	8,208,027	144	6982	20.1	14.3	16.4	6.8	4.1	36.5
Farming-Grazing Belt.....	18,753,009	122	2122	30.8	32.8	8.4	4.5	3.8	18.7
Spring Wheat Section...	8,763,110	163	1975	40.0	40.3	5.2	6.0	5.2	13.4
Corn Section...........	6,828,800	132	2410	22.0	35.5	13.8	2.5	2.1	20.5
Winter Wheat Section..	2,261,819	84	2114	32.7	34.3	12.3	2.8	3.1	34.5
Cotton Section.........	899,280	42	1808	2.4	1.7	14.4	9.2	6.4	37.0
Grazing-Forage Crop Belt.	6,372,947	40	848	27.3	20.2	7.1	3.7	2.5	15.0
Spring Wheat Section...	3,732,048	39	588	32.2	23.7	4.8	4.4	3.1	12.0
Corn Section (a)........	1,382,175	88	2294	30.3	26.5	11.1	2.9	1.9	18.0
Winter Wheat Section..	943,730	29	786	12.2	15.0	16.4	2.9	3.0	26.6
Cotton Section (a)......	314,994	25	1170	0.6	0.2	9.8	1.2	0.6	28.5
Arid & Bad Land Areas (a)	2,882,157	26	690	26.2	15.4	7.2	2.9	1.9	18.0
Spring Wheat Section...	1,479,133	24	306	33.5	21.6	3.5	3.4	2.4	10.0
Corn Section...........	482,789	120	5270	32.1	19.4	12.9	2.8	1.5	24.5
Winter Wheat Section..	824,847	32	1184	12.8	11.5	16.3	2.5	2.0	22.2
Cotton Section.........	95,388	5	276	0.3	0.2	14.7	1.0	0.5	36.9

(a) A large proportion of the acreage is irrigated, especially in the North Platte Valley included in the Corn
(b) In the Central Plains especially much of the corn grown for grain is also used for forage, consequently there
(c) Less than one-tenth of one per cent.

I

REGION

IMPORTANCE OF THE PRINCIPAL CROPS, AND YIELD PER ACRE, 1919

Barley Percentage of		Barley Yield Per Acre Bushels	Rye Percentage of		Rye Yield Per Acre Bushels	Corn Grain (b) Percentage of		Corn Grain Yield Per Acre Bushels	Corn Silage Percentage of		Corn Silage Yield Per Acre Tons
Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops	
3.2	2.4	15.4	4.3	1.9	7.4	12.4	14.3	20.4	0.4	0.7	4.4
3.4	2.5	16.4	3.9	1.7	7.9	13.6	15.4	22.1	0.5	0.7	4.6
6.9	6.0	14.2	9.2	5.3	7.5	3.5	5.7	24.0	0.4	0.9	5.1
2.0	1.7	20.6	1.3	0.7	9.9	34.7	41.7	23.2	0.4	0.7	4.9
1.8	1.8	22.7	1.1	0.6	9.3	8.7	7.6	15.2	0.8	1.1	4.0
0.3	0.2	29.2	0.1	0.1	14.1	10.2	7.1	25.0	0.1	0.1	6.0
3.4	2.7	12.3	6.2	3.6	6.8	10.4	12.3	15.2	0.2	0.2	3.1
4.4	4.2	9.9	10.2	7.6	6.2	3.1	5.5	16.0	0.1	0.2	2.5
2.1	2.1	15.6	3.9	2.6	8.7	21.1	22.0	14.0	0.1	0.2	2.9
4.3	3.0	16.6	0.4	0.4	13.2	4.1	4.0	16.8	0.3	0.3	3.4
0.1	0.1	26.7	(c)	(c)	12.5	15.1	12.0	25.4	0.2	0.3	5.5
1.1	0.9	13.3	3.0	1.2	5.5	9.6	10.7	16.2	0.6	0.9	3.4
0.8	0.7	10.2	3.6	1.5	4.2	3.4	3.8	11.8	0.1	0.2	2.9
1.9	1.4	15.5	3.5	1.5	7.8	19.6	14.3	13.6	1.9	2.4	3.4
1.3	1.0	16.4	0.8	0.6	13.1	16.0	17.9	20.2	0.4	0.5	3.8
(c)	(c)	7.2	(c)	(c)	14.5	19.8	15.7	27.2	0.9	0.8	4.4
1.4	1.3	19.0	2.5	0.5	3.7	6.9	5.1	14.2	0.8	1.5	5.2
0.7	0.6	7.9	4.3	1.7	3.2	2.5	2.8	9.9	0.1	0.2	2.5
3.4	2.1	20.7	0.8	0.1	3.8	5.1	1.5	9.2	2.2	2.5	5.0
1.6	1.4	25.5	0.6	0.2	8.7	14.7	8.8	15.9	1.2	1.9	5.8
(c)	(c)	21.2	(c)	(c)	15.0	15.0	7.0	19.1	0.4	0.3	3.9

Section, and in the Cotton Sections of Southern Texas.
is some duplication of acreage in these items.

TABLE I—

GREAT PLAINS

	Corn Forage (b) Percentage of		Corn Forage Yield Per Acre Tons	Sorghum Grain Percentage of		Sorghum Grain Yield Per Acre Bushels	Sorghum Forage Percentage of		Sorghum Forage Yield Per Acre Tons
	Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops	
Great Plains Total..........	1.9	1.5	1.6	3.5	3.6	20.4	3.7	3.5	1.6
Black-Earth Belt............	1.8	1.5	1.8	3.5	3.3	20.3	3.3	3.0	1.7
Spring Wheat Section.....	2.4	3.6	2.2	(b)	(b)	6.3	(b)	0.1	2.7
Corn Section.............	1.4	1.1	1.8	0.7	0.1	14.9	2.0	1.6	2.2
Winter Wheat Section.....	2.1	1.0	1.4	7.0	5.4	15.0	6.3	5.5	1.7
Cotton Section...........	0.4	0.1	0.8	12.0	7.6	26.2	8.3	4.9	1.6
Farming-Grazing Belt.......	1.6	1.3	1.2	4.0	5.7	20.6	4.0	5.2	1.5
Spring Wheat Section.....	1.5	2.1	1.2	(b)	(b)	1.6	0.1	0.1	1.6
Corn Section.............	2.1	1.5	1.2	(b)	(b)	8.4	2.9	2.5	1.4
Winter Wheat Section.....	0.8	0.5	1.4	27.2	25.8	19.2	19.5	19.1	1.6
Cotton Section...........	0.4	0.1	0.9	15.0	10.8	26.8	11.2	7.8	1.6
Grazing-Forage Crop Belt...	3.1	1.9	0.9	3.7	4.7	21.0	5.4	5.7	1.5
Spring Wheat Section.....	2.8	2.1	0.8	(b)	(b)	1.5	0.2	0.3	1.3
Corn Section.............	5.3	2.9	1.1	0.6	0.3	15.4	6.1	3.8	1.3
Winter Wheat Section.....	1.7	0.8	1.0	20.2	19.5	20.4	22.6	18.3	1.5
Cotton Section...........	1.0	0.4	1.1	12.4	7.7	25.0	12.1	9.2	1.8
Arid & Bad Land Areas (a)..	3.5	1.5	0.9	1.4	1.1	17.1	6.0	4.0	1.3
Spring Wheat Section.....	3.3	2.3	0.6	(b)	(b)	4.3	0.1	0.2	1.2
Corn Section.............	3.8	0.9	0.8	(b)	(b)	18.2	2.5	0.7	1.0
Winter Wheat Section.....	3.8	1.6	1.2	4.4	2.5	17.0	15.9	7.5	1.3
Cotton Section...........	1.3	0.6	1.3	3.5	1.4	18.8	28.1	10.7	1.1

(a) A large proportion of the acreage is irrigated.
(b) Less than 1-10 of one per cent.

Continued

REGION

Tame Hay Percentage of		Tame Hay Yield Per Acre Tons	Wild Hay Percentage of		Wild Hay Yield Per Acre Tons	Cotton Percentage of		Cotton Yield Per Acre Bales	All Other Crops Percentage of	
Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops		Acreage of all Crops	Value of all Crops
5.0	7.1	1.5	11.5	5.0	0.7	4.2	10.9	0.36	5.3	9.3
4.2	5.0	1.6	7.4	3.7	0.9	5.4	13.0	0.37	3.4	7.2
3.4	4.9	1.2	11.2	8.2	1.0				5.8	11.6
7.4	9.2	1.7	11.6	5.2	0.9				1.9	3.1
3.6	4.9	1.7	2.0	1.1	1.0	0.5	1.3	0.39	2.1	3.1
1.3	1.3	1.6	0.2	0.1	1.2	37.6	49.4	0.37	2.7	10.7
3.5	6.1	1.2	23.2	12.0	0.6	1.9	5.5	0.29	6.4	8.6
3.1	8.2	1.0	22.0	16.3	0.6				9.4	10.2
4.7	6.9	1.4	34.7	17.0	0.7				3.8	7.6
2.2	2.5	1.5	1.7	0.9	1.0	0.3	0.7	0.31	3.5	4.9
1.7	2.4	1.4	0.1	(b)	1.0	39.3	45.1	0.28	5.1	13.3
10.6	20.6	1.6	16.2	5.4	0.4	1.9	4.7	0.30	14.0	20.8
11.4	30.5	1.4	25.2	10.6	0.4				15.8	23.5
14.0	20.5	1.9	3.6	1.9	0.8				10.4	22.4
5.6	8.6	1.6	3.3	1.8	0.9	0.4	1.0	0.38	12.4	12.1
2.1	3.1	2.4	0.1	0.1	1.1	37.1	40.6	0.29	12.6	21.5
19.9	29.9	1.8	9.6	2.4	0.4	1.3	2.1	0.24	17.6	33.1
17.4	48.4	1.2	15.8	7.1	0.3				18.9	12.8
22.7	21.2	2.2	3.1	0.7	0.6				21.4	49.2
24.6	29.2	2.4	3.3	1.1	0.7	0.1	0.1	0.4	14.4	32.2
3.8	3.4	1.8	0.4	0.1	1.0	39.6	30.3	0.24	6.5	45.4

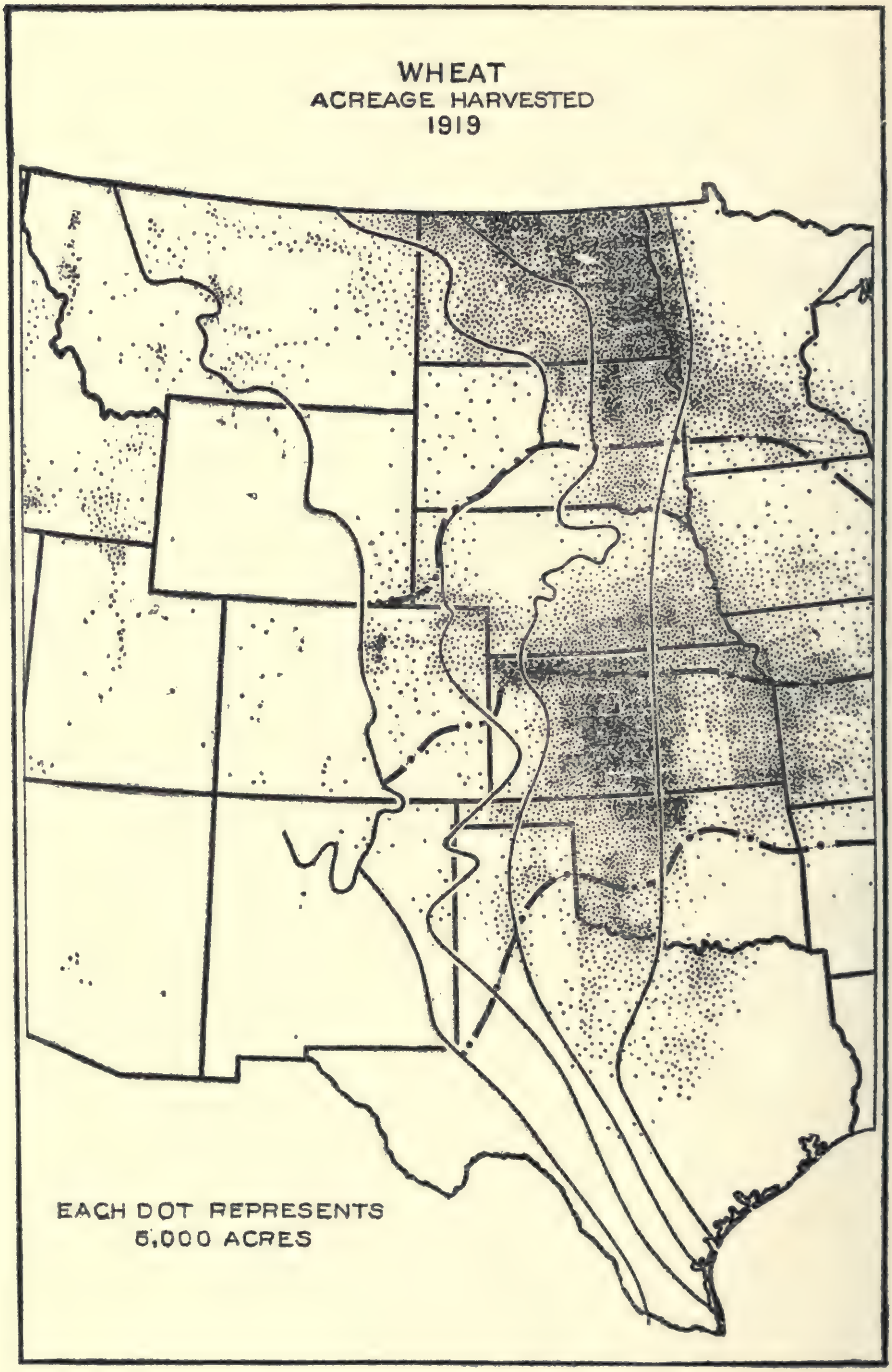


Fig. 5.—Distribution of Wheat Production.

The spring wheat section of the sub-humid Black-Earth belt contains nearly half of the acreage of spring wheat in the United States and 15 per cent more is found in the spring wheat section of the semi-arid Farming-grazing belt to the west. The winter wheat section of the Black-Earth belt contains about 30 per cent of the winter wheat acreage in the United States, and 4 per cent more is found in the Farming-grazing belt. The average yield of spring wheat per acre in the Black-Earth belt was 8 bushels in 1919, and in the Farming-grazing belt it was 5.2 bushels. The 10-year average yield per acre of spring wheat in the North Dakota portion of the Black-Earth belt is about 11 bushels, as compared with 9 bushels in the Farming-grazing belt. A small acreage of spring wheat is found in the Grazing-forage crop belt. The average yield of the acreage harvested in this belt in 1919 was 4.8 bushels, and over half the acreage planted was not harvested. The 10-year average yield per acre of spring wheat in the three North Dakota counties in this dry belt is 8 bushels, which is probably above the average for the belt. The ten-year average yield per acre of winter wheat in the Kansas portion of the Black-Earth belt is 11 bushels, of the Farming-grazing belt 8 bushels, and of the Grazing-forage crop belt 6 bushels.

These average yields in the semi-arid Farming-grazing and Grazing-forage crop belts of about 9 and 7 bushels, respectively, of spring wheat, and about 8 and 6 bushels per acre, respectively, of winter wheat, do not tell the whole story. The variations in acre-yield are perhaps of greater significance. Figure 6 shows the average yields of all varieties of spring wheat at the U. S. Department of Agriculture Experiment Stations at Dickinson, No. Dak., in the Farming-grazing belt, and at Bellefourche (Newell), So. Dak., in the Grazing-forage crop belt; also of winter wheat at Akron, Colo., on the western edge of the Farming-grazing belt and at Hays, Kan., in the Black-Earth belt. It will be noted that the acre yields at Bellefourche have ranged from nothing to nearly 60 bushels per acre, varying largely with the precipitation, and that at the other stations the variations in yield are very great. Droughts at critical times and severe attacks of rust, as well as deficient yearly precipitation, account for the low yields in several years.

The high yields obtained in the moist seasons 1914, 1915, and 1916 encouraged hosts of homesteaders to flow into these semi-arid grazing belts in the western portions of the Dakotas and in Montana, file their entries, build their shacks, break up 40 acres or more of the short-grass sod, and seed the land to wheat. Then the successive crop failures during the dry seasons 1917, 1918, and 1919 blasted their hopes and

drove many to the villages in the irrigated areas, or back home, leaving the fields to grow up to Russian thistles and other weeds. The permanent use of the land for crops seems to depend as much on the frequency and severity of the dry seasons as on the average yields obtained in a series of years, probably because several dry seasons exhaust the crop farmer's capital.

Oats, Barley, Rye and Flax.—Rye, barley, and flax are also important crops in the spring wheat section of the Great Plains, while oats are of greatest importance in the Corn Belt section (Fig. 7). Oats are grown, however, all the way from Canada to the Edwards Plateau, mostly in the Black-Earth belt. The oats and barley are grown mostly for local use as feed, and should be considered as part of a livestock rather than a grain system of farming.

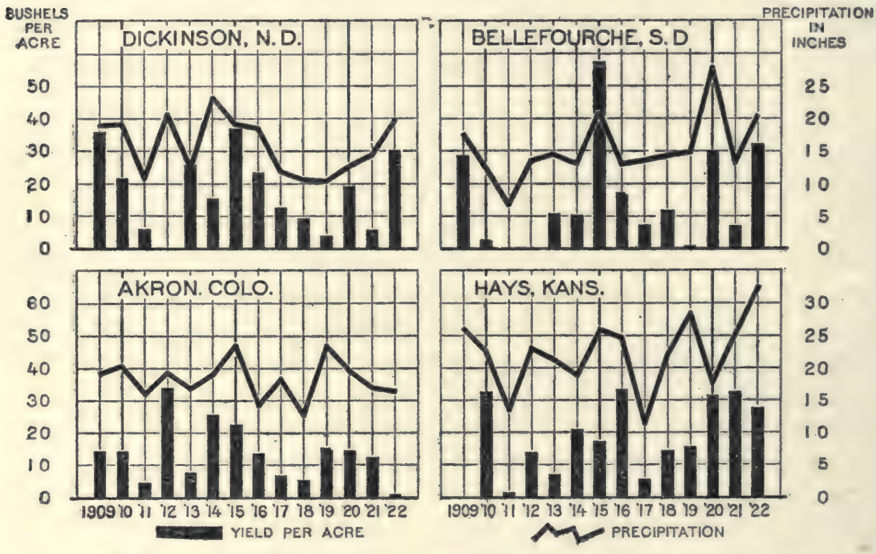


FIG. 6.—Yields in Relation to Precipitation at Selected Stations.

The increase in rye acreage during the war years was rapid, owing to the high prices occasioned by the European demand, and also to the fact that rye is the only small grain crop in this northern area that can be planted in the fall, and thus relieve the heavy demand in the spring for labor, which was very scarce during the war. The acreage of barley decreased in the spring wheat section of the Great Plains between 1909 and 1919, but increased in the winter wheat section of Kansas and Oklahoma, probably owing in part to the labor situation and in part to the winter killing of winter wheat. Barley is a spring-sown crop. Nearly all the flax produced in the United

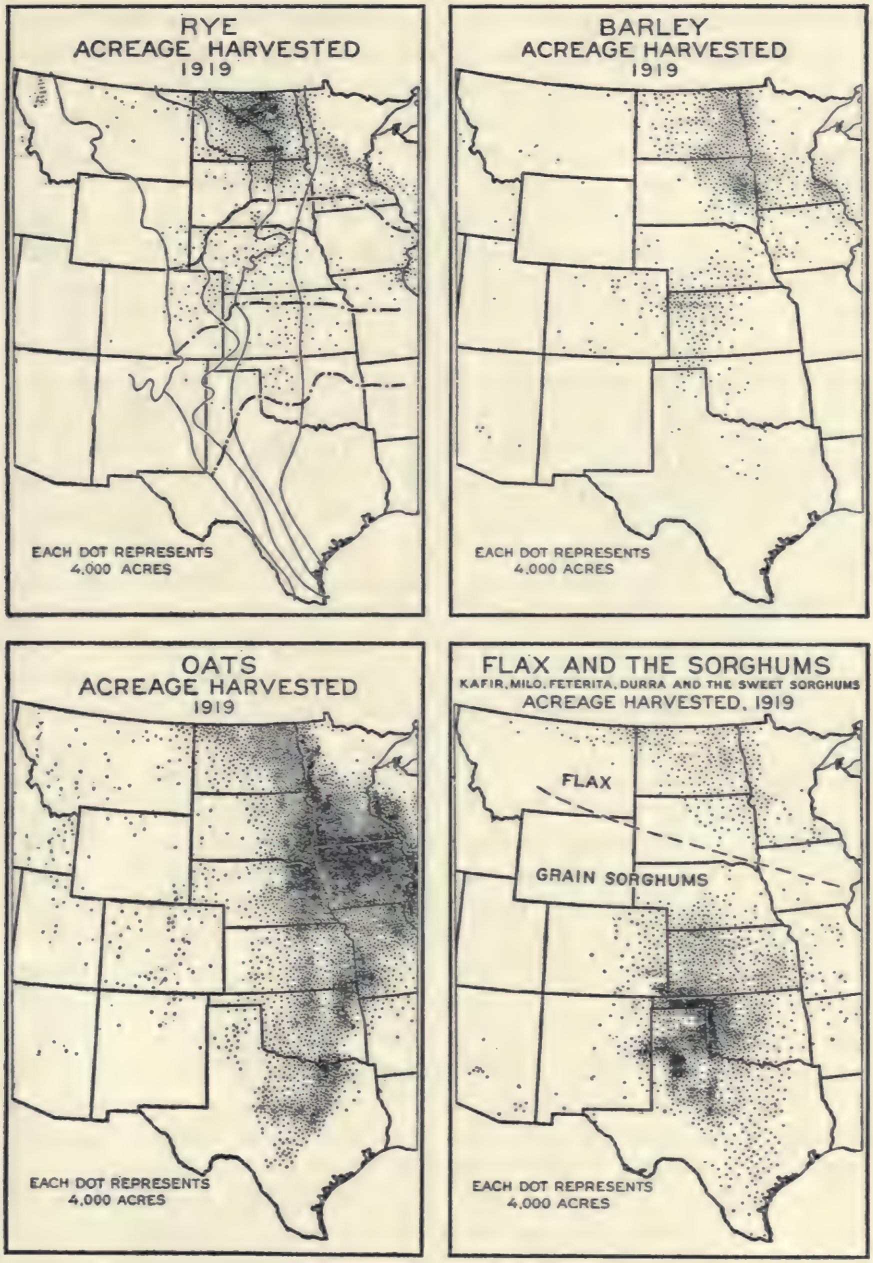


FIG. 7.—Distribution of Small Grains Other Than Wheat.

States is grown in the spring wheat section of the Great Plains, and the acreage decreased about 40 per cent between 1909 and 1919. Flax is a "new land" crop, owing largely to flax-wilt, a disease that persists in the soil for many years after infection. Much of the flax in the Black-Earth belt especially is now grown on newly broken rough or gravelly land, since there is little other virgin land in this section of the Great Plains.

Corn and the Grain Sorghums.—The second most important crop in the Great Plains region is corn, contributing about 14 per cent of the acreage and 16.5 per cent of the value of all crops. It is more important than wheat or hay in most of the Nebraska portion of the Black-Earth belt, in the southeastern corner of South Dakota, and in the northern tier of counties in Kansas; also in a band of counties extending entirely across the Plains portion of Colorado southwesterly from Kit Carson to Pueblo (Fig. 8.). It decreases somewhat in relative importance from east to west, occupying about 15 per cent of the crop land in the Black-Earth belt and about 10 per cent in the arid areas. Corn for grain, however, decreases from 13.6 per cent of the crop land in the Black-Earth belt to 6.9 per cent in the Arid Areas, whereas corn cut for forage increases from 1.8 per cent to 3.5 per cent. The average yields per acre of corn 1919-1922 in 7 counties in the Black-Earth section of Nebraska and Kansas was 25 bushels; in the Farming-grazing belt, 18 bushels; and in the Grazing-forage crop belt in Kansas, 16 bushels.

Very little corn is grown in North Dakota and Montana, except for forage or silage; and in southwestern Kansas, southeastern Colorado, western Oklahoma and Texas, and eastern New Mexico it is partially replaced by the sorghums, which are grown for both grain and forage (Fig. 7). In the winter wheat section of the Black-Earth belt the sorghums constitute 13 per cent of the crop land, and in the cotton section over 20 per cent. These percentages increase in the Farming-grazing belt to 47 per cent for the winter wheat and 26 per cent for the cotton section, and the percentages are almost the same for the corresponding sections of the Grazing-forage belt. The yields per acre both of grain and forage in 1919 were practically the same in these three moisture belts, but the yield of grain in the cotton section of each belt was much higher than in the winter wheat section.

These two crops, corn and the sorghums, are the most dependable crops in the Farming-grazing and Grazing-forage crop belts, and seem destined to become the dominant crops in a permanent system of agriculture in the northern and southern portions of these belts respectively.

Hay.—Hay is the third crop in value in the Great Plains region,

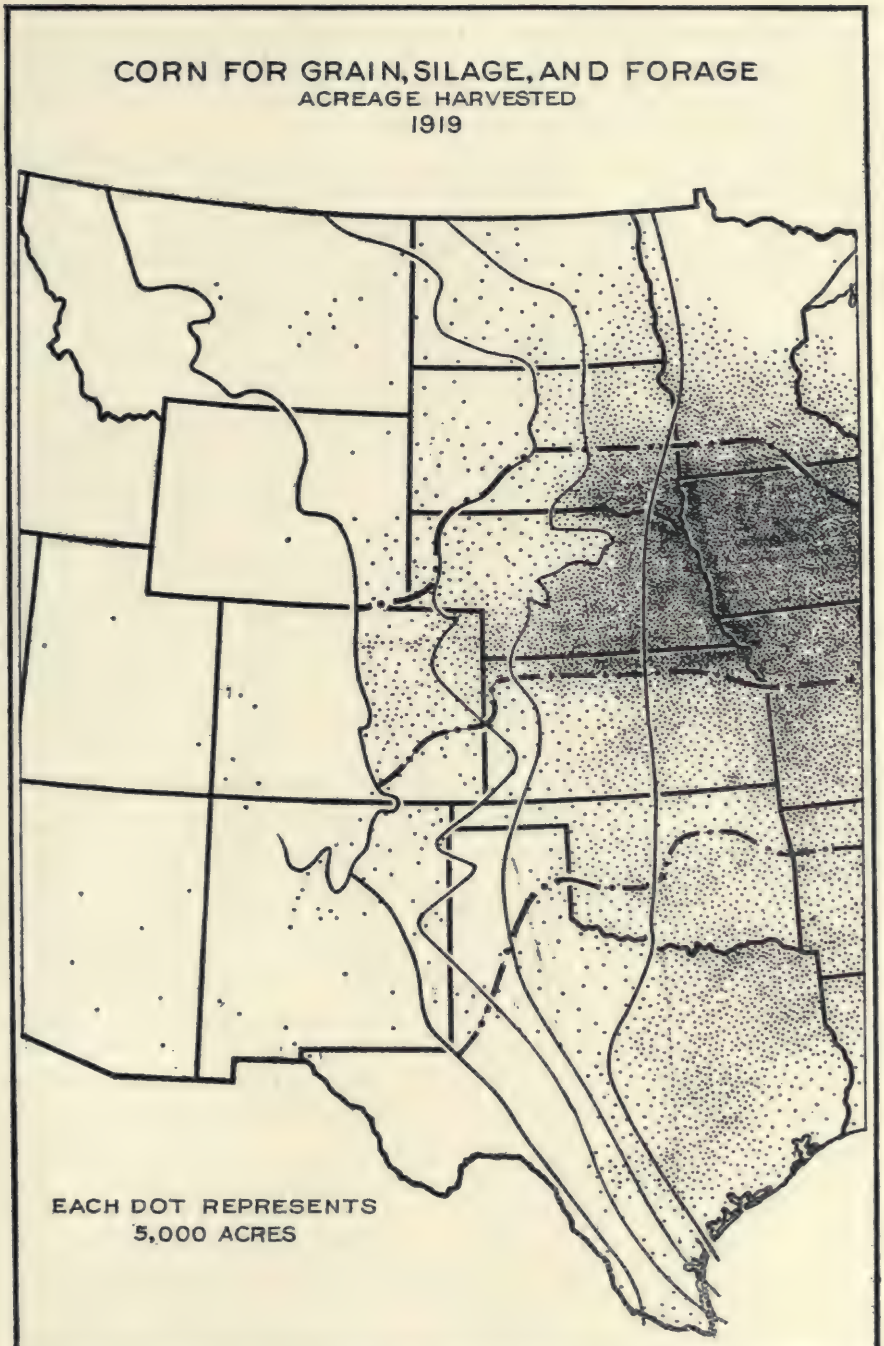


FIG. 8.—Distribution of Corn Production.

contributing about 16 per cent of the acreage, and 12 per cent of the value of all crops in 1919. In the Black-Earth belt hay constitutes 12 per cent of the acreage of all crops, and in both the Farming-grazing and Grazing-forage crop belts 27 per cent (Fig. 9).

Timothy and clover, the great hay crops of the eastern states north of the Cotton Belt, are unimportant in the Great Plains region. Timothy extends in thinly scattered fields about two-thirds across the Black-Earth belt in the Dakotas, just touches the eastern boundary of this belt in Nebraska, and does not reach it in Kansas. Red clover laps over the eastern margin of the Black-Earth belt only a few miles in the Dakotas and Nebraska, and peters out a hundred miles east of the belt in Kansas (Fig. 10).

The all important hay crop in the Dakotas and the Sand Hill area of Nebraska is wild hay, composed mostly of the native andropogons, locally called blue-stem, frequently mixed with wheat grass and needle grass (Fig. 10). In good seasons the acre yield of this hay in the sub-humid Black-Earth belt is almost equal to that of timothy in the humid East. This wild hay during the days of the cattlemen was practically the only crop secured in the Great Plains, and it has been the salvation of many of the homesteaders in the semi-arid belts in recent years. It is the principal feed, other than pasture, depended upon to keep the stock through the winter. Wild hay constitutes 7 per cent of the acreage of all crops in the Black-Earth belt, 23 per cent in the Farming-grazing belt, 16 per cent in the Grazing-forage belt, and less than 10 per cent in the arid and Badland areas.

In the southern Nebraska and Kansas portions of the Black-Earth belt alfalfa is the dominant hay crop (Fig. 10). This central section of the Black-Earth belt, and the land to the east as far as the Missouri river, includes the only large area of alfalfa in the United States grown under natural rainfall. The rainfall here is usually sufficient to produce fair yields of hay, but insufficient to leach the lime out of the sub-soil. Lime in the soil is essential to successful alfalfa culture.

Alfalfa is the principal haycrop also in the irrigated districts which are located mostly in the arid areas and in the Grazing-forage Crop belt.

Another important class of hay in this Great Plains region, especially in the Dakotas and Montana, and even more in Canada, consists of the small grains cut for hay. Frequently, wheat, barley, oats, or even rye may be sown for this purpose, but more commonly these fields are cut for hay when the crop is not worth harvesting for grain. In 1919, which was one of the driest years ever known in the northern plains, an unusually large acreage of grain was cut for hay (Fig. 10).

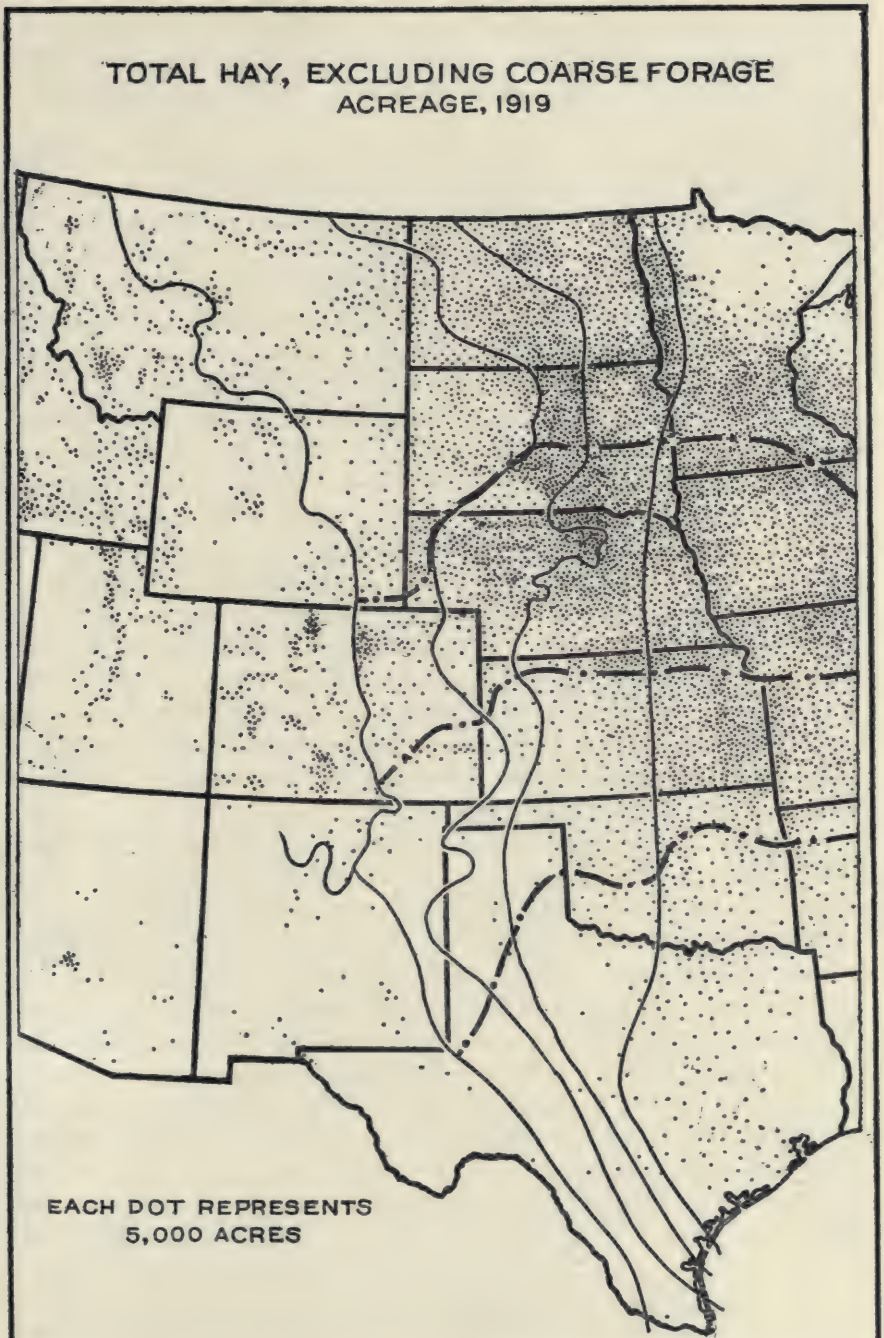


FIG. 9.—Distribution of Hay Production.

Brome grass and sweet clover are relatively new hay crops of promise in the Great Plains region, especially in the spring wheat section. Although the acreage of both crops is small, it is increasing rapidly.

Cotton.—Only one other crop need be mentioned in this brief survey, namely, cotton, which constituted nearly half the value of all crops in the cotton section of the Black-Earth belt in 1919, and over 40 per cent in the cotton section of both the semi-arid belts (Fig. 11). Cotton has been pressing west and northwest until it has now climbed onto the Staked Plains of the Texas Panhandle, and is grown almost as far northwest as Amarillo. The winters on these plains are severe, and there is also no forest and little trash about the farms for the boll weevil to hibernate in, so that in this respect the Great Plains possess an advantage over other parts of the South. But under the dry conditions the plants are small and the yields are low, and a profit can be obtained only by an extensive type of culture and greater use of machinery than is common in the Cotton Belt proper.

Cotton is becoming the leading crop in the southeastern portion of the Staked Plains, on the Red Prairies, along the eastern margin of the Edwards Plateau, and throughout the Gulf Coastal Plain area. There is a large area of land in these districts that may be put into cotton if the price remains high enough to compensate for the usually low acre-yields. Should this occur, the southern Plains, instead of being the most sparsely, would become the most densely populated portion of the Great Plains region.

The Farm Garden.—In this connection the importance of the farm garden and other farm contributions to the family living should be noted. In 1919 the average value of vegetables grown for home use only, including potatoes, was $78 per farm in Montana, $67 in North Dakota, $66 in South Dakota, $58 in Nebraska, $52 in Kansas, $62 in Oklahoma and $60 in Texas. This is considerably less than in New England and the North Atlantic States, but almost equal to the average for the United States. A farm survey in North Dakota shows that in 1921 on 123 farms scattered throughout the state the average value of the food furnished the family by the farm was $524, whereas groceries bought amounted to $296. The value of the potatoes and vegetables furnished by the farm was $68, poultry $81, pork $63, beef $33, while dairy products, amounting to $267, were almost half the total.*

* "Cost of Production and Farm Organization on 123 Farms," by Willard, Metzger and Thorfinnson, North Dakota Agricultural Experiment Station, Bulletin 165, page 97. This bulletin presents very valuable data on agriculture in the Spring Wheat Section of the Great Plains.

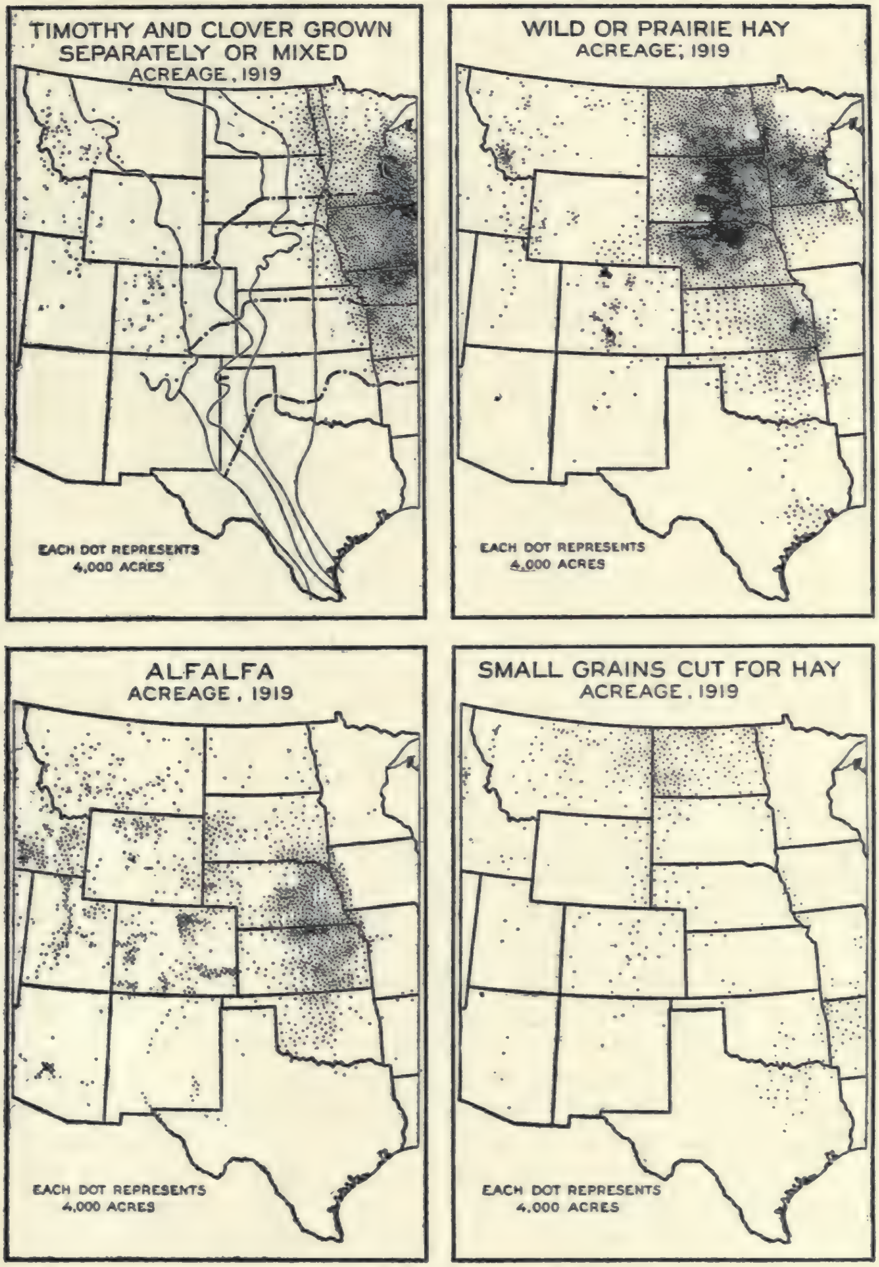


FIG. 10.—Distribution of Four Important Hay Crops.

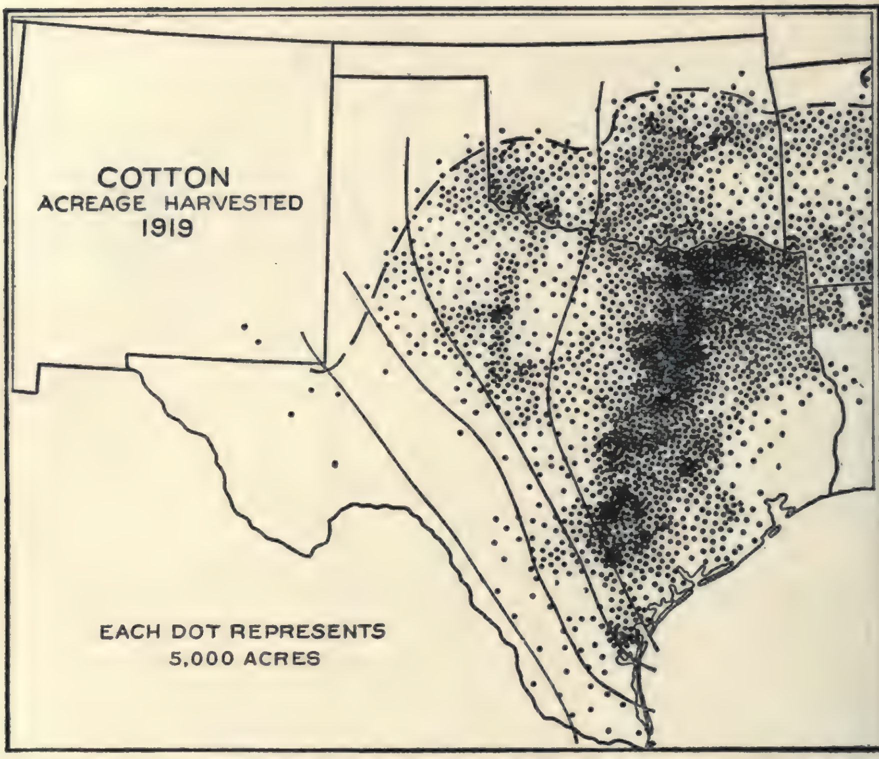


FIG. 11.—Distribution of Cotton Acreage.

Probably one of the principal reasons why European immigrants appear more successful as settlers than native Americans in the semi-arid belts especially, and seem better able to survive the periods of drought, is because of their gardens, which are made to contribute a large part of the family living. Many of the native American farmers seem to inherit, in a measure, the cattleman's dislike of hand labor, especially gardening, which seems to him a petty affair unworthy of his time. The large wheat farmer also has little time for gardening in the spring when putting in his wheat. But as farming in the Great Plains becomes less specialized and the seasonal needs of labor more uniform, greater attention will undoubtedly be given to the farm garden and the livestock which contribute directly to the family living.

PASTURE IN THE GREAT PLAINS.—In the Black-Earth belt about 31 per cent of the land area is used only for pasture, as compared with 45 per cent in crops, but the annual rental value per acre of the pasture probably does not exceed a third that of the crop land. In the Farming-

grazing belt about 60 per cent of the land area is in pasture, and 21 per cent in crops; while in the Grazing-forage crop belt about 75 per cent is in pasture and 7 per cent is in crops. The rental value of the pasture in these belts is perhaps one-fourth and one-fifth, respectively, that of the crop land. Multiplying the acreage by the average rental value per acre it appears that the aggregate rental value of the pasture land in the Black-Earth belt is less than one-fourth that of the crop land, and in the Farming-grazing belt about three-fourths. In the Grazing-forage crop belt, excluding the irrigated land, the annual aggregate rental value of the pasture land is twice that of the crop land.

Composition of the Pasture.—In the Black-Earth belt the pasture is composed mostly of timothy and the wild prairie grasses in the eastern portion of the spring wheat section; brome grass and the wild grasses, mostly needle grass, wheat grass and blue-stem, in the western portion. In the corn section of the Black-Earth belt Kentucky bluegrass becomes an important pasture grass, and in the eastern portion of the belt in Nebraska it is the dominant grass. In Kansas it recedes eastward and is replaced by alfalfa and wild prairie grass in the northern portion of the state, while in the southern portion practically all the pasture is composed of the native grasses, mostly buffalo grass, blue-stem, and bunch grass. In Texas mesquite grass displaces buffalo grass from Amarillo southward. Johnson grass is also used for pasture in the eastern portion of the Black-Earth belt in Texas and Oklahoma, and Sudan grass in the western portion.

In the semi-arid Farming-grazing and Grazing-forage crop belts the pasture is composed almost wholly of the native grasses. Grama grass, wheat grass, and needle grass are most important in Montana, Wyoming and the Dakotas, buffalo grass and grama grass in Nebraska, Kansas and Colorado, with bunch grass (andropogons) on the sandy soils; and in Texas mesquite grass becomes dominant.

Carrying Capacity of the Pasture.—The carrying capacity of the wild grass pasture in the Black-Earth belt ranges, in general, from 1½ to 4 acres per cow or steer in the spring wheat area, and from 3 to 15 acres in the winter wheat area, but on the Edwards Plateau and Gulf Coastal Plain portions of this Black-Earth belt it diminishes to 15 to 20 acres per cow or steer (Fig. 12). In the Farming-grazing belt from 5 to 15 acres are required in the Dakota, Nebraska, and Kansas portions, but from 15 to 25 acres in the Texas portion; and in the Grazing-forage crop belt from 15 to 25 acres throughout. In the arid grazing areas 20 to 40 acres per cow or steer are usually needed. In these arid districts, however, sheep probably graze a greater acreage than cattle.

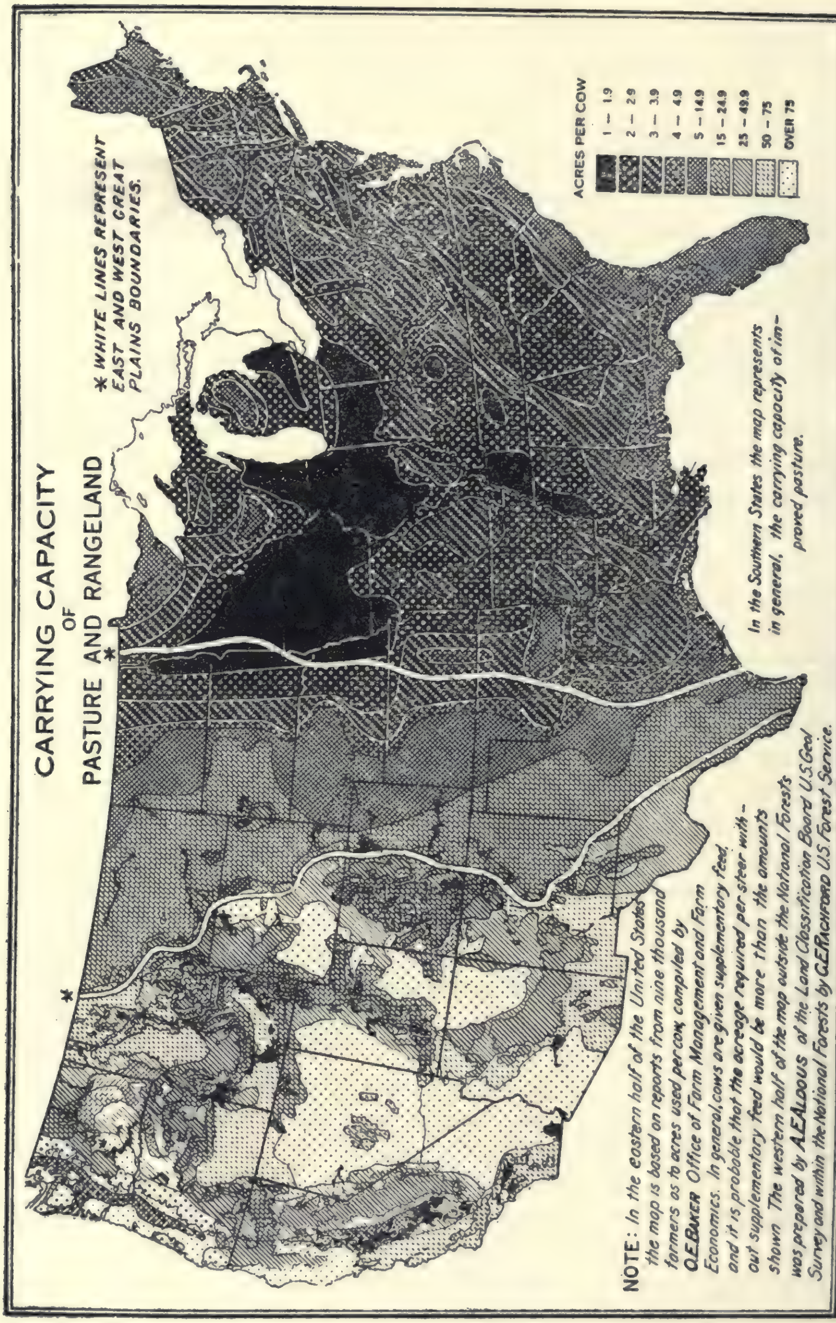


FIG. 12.—Carrying Capacity of Pasture and Range Land.

The decrease in carrying capacity of the pasture from north to south within the same moisture belt should be noted. Soil color and crop yields show close correlation, but carrying capacity of pasture diminishes more rapidly than crop yields with increase in temperature along lines of equal rainfall. For instance, the line of 15 acres per cow carrying capacity crosses the Canadian boundary near Opheim, Mont., where the average annual precipitation is about 14 inches, and ends at Corpus Christi, Tex., on the Gulf of Mexico, where the annual precipitation is 25 inches, crossing both the Farming-grazing and the Black-Earth belts (compare Fig. 12 with Fig. 1). Probably the seasonal distribution of rainfall, especially the summer drought in southern Texas, is an important factor.

Live Stock in the Great Plains.—The Great Plains were originally the feeding grounds of vast herds of buffalo. During the last third of the nineteenth century the buffalo were replaced by cattle, and today cattle raising remains the dominant agricultural enterprise in the semi-arid portions of the Plains. The Black-Earth belt, except the Corn Belt portion, has become and will continue to be for some years primarily a cash crop country, and probably the value of the wheat and other cash crops in the Farming-grazing belt will equal the value of the annual production of live stock and live stock products for several years. But in the Grazing-forage crop belt and in the non-irrigated portions of the arid areas live stock production will undoubtedly remain the principal industry. The density of distribution of live stock, on the basis both of animal units and of value per square mile, and the relative importance of the different classes of live stock, are shown for the four belts in Table II.

It will be noted that in the Black-Earth belt the number of animal units per square mile varied from 85 in the corn section to 40 in the cotton section, with an average density for the belt of 54 per square mile. In the Farming-grazing belt the number per square mile varied from 37 in the corn section to 30 in the winter wheat section, and averaged 33 for the entire belt. In the Grazing-forage crop belt the greatest density, 38 per square mile, was likewise in the corn section, which contains considerable irrigated land, and the least, 21 per square mile, in the spring wheat section, the average for the belt being 24 per square mile. In the Arid and Badlands areas, including irrigated districts, the average number of animal units per square mile was 22. This is nearly 30 acres per animal unit, as compared with about 8 acres in the corn section of the Black-Earth belt.*

* An animal unit equals 1 horse, 1 cow or steer, 5 swine, 7 sheep and 100 poultry.

TABLE

GREAT PLAINS

LIVESTOCK DENSITY AND

	Number of Animal Units (3)	Number of Animal Units Per. Sq. Mile	Value of Live-stock Per. Sq. Mile	Beef Cattle Percentage of		Dairy Cattle Percentage of	
				Total Animal Units	Total Live-stock Value	Total Animal Units	Total Live-stock Value
Great Plains Total.......	22,628,119	36	2280	50.3	41.7	14.0	11.7
Black-Earth Belt.........	11,257,536	54	3535	43.4	32.8	18.3	14.3
Spring Wheat Section..	2,485,351	45	3109	28.4	19.7	27.4	20.8
Corn Section..........	3,461,276	85	5582	43.2	31.6	16.1	12.8
Winter Wheat Section..	3,020,394	52	3306	49.3	39.2	15.6	12.5
Cotton Section.........	2,290,515	40	2710	52.0	41.1	15.4	11.6
Farming-Grazing Belt....	5,097,132	33	1965	57.0	50.9	11.0	9.9
Spring Wheat Section..	1,651,401	31	1847	41.0	34.5	19.5	17.1
Corn Section..........	1,901,471	37	2046	63.8	58.5	7.4	7.1
Winter Wheat Section..	808,056	30	1855	71.0	63.4	7.1	6.2
Cotton Section.........	736,204	34	2201	60.3	55.5	6.0	5.0
Grazing-Forage Crop Belt.	3,796,701	24	1513	56.7	50.8	9.3	8.9
Spring Wheat Section..	2,020,366	21	1333	52.5	47.6	9.0	8.6
Corn Section (3).......	592,065	38	2373	49.9	42.9	18.6	17.5
Winter Wheat.........	749,478	23	1324	74.4	69.6	5.3	5.1
Cotton Section (3).....	434,792	34	2289	55.3	47.0	4.9	5.0
Arid & Bad Land Areas(3)	2,476,748	22	1410	58.1	52.6	7.2	6.9
Spring Wheat Section..	1,144,243	19	1193	52.7	47.6	7.3	7.2
Corn Section..........	207,964	52	3837	35.2	32.6	16.2	13.2
Winter Wheat Section...	649,582	25	1461	64.4	58.2	8.7	8.6
Cotton Section.........	474,959	25	1529	72.7	68.7	1.0	0.9

(1) An animal unit equals one horse, mule, cow or steer, five swine, seven sheep or goats, underrates swine, sheep, goats and poultry in this region.

(2) Less than one-tenth of one per cent.

(3) Includes irrigated land.

II
REGION

RELATIVE IMPORTANCE

Horses and Mules Percentage of		Sheep Percentage of		Goats Percentage of		Swine Percentage of		Poultry Percentage of	
Total Animal Units	Total Live-stock Value	Total Animal Units	Total Live-stock Value	Total Animal Units	Total Live-stock Value	Total Animal Units	Total Live-stock Value	Total Animal Units	Total Live-stock Value
23.4	29.5	4.3	5.6	0.8	0.6	5.4	8.3	1.8	2.4
25.8	35.1	1.5	1.8	0.3	0.1	8.0	12.2	2.6	3.4
32.6	42.9	2.2	2.7	(2)	(2)	7.0	11.0	2.3	2.8
22.0	26.9	1.3	1.6	(2)	(2)	14.7	23.4	2.8	3.5
27.3	37.7	0.6	0.7	0.1	(2)	4.4	5.4	2.8	4.0
22.8	35.6	2.1	2.4	1.2	0.7	4.1	5.1	2.2	3.1
22.3	25.5	2.9	4.1	1.5	1.1	4.1	6.4	1.2	1.8
30.9	36.6	3.1	4.1	(2)	(2)	4.1	6.1	1.4	1.9
21.2	21.2	0.8	1.1	(2)	(2)	5.7	9.9	1.2	1.9
17.2	23.1	1.5	1.9	(2)	(2)	2.1	3.3	1.1	1.8
11.4	15.1	9.3	13.3	10.1	6.9	2.1	2.6	0.7	1.1
20.8	23.1	9.0	12.2	1.4	1.0	1.9	2.6	0.8	1.3
26.8	28.0	9.2	12.2	(2)	(2)	1.7	2.3	0.8	1.2
17.1	21.2	9.5	10.8	(2)	(2)	3.4	5.0	1.4	2.2
13.7	16.8	4.1	4.9	0.4	0.2	1.3	2.1	0.7	1.1
10.3	12.9	16.1	24.5	11.4	7.7	1.4	1.7	0.6	1.0
18.7	20.1	12.4	16.4	1.4	0.9	1.5	1.9	0.7	1.0
25.9	25.1	12.2	17.6	(2)	(2)	1.3	1.6	0.6	1.0
21.3	27.4	22.3	21.0	(2)	(2)	3.6	3.7	1.4	1.8
15.1	19.0	8.4	9.3	0.4	0.2	2.0	3.0	0.8	1.4
5.0	4.8	13.8	20.2	7.0	4.6	0.4	0.4	0.1	0.2

and 100 poultry. This customary ratio is based on feed requirements in the east and probably

Cattle.—In 1920 cattle constituted 64 per cent of the total animal units in the Great Plains region, and 53 per cent of the value of all livestock. Beef cattle were more important than dairy cattle in all portions of the region, except in the spring wheat section of the Black-Earth belt, where the two classes of cattle were of equal importance (compare Figs. 13 and 14). Beef cattle constituted half of the total animal units in the Great Plains region as a whole, whereas dairy cattle contributed only 14 per cent of the animal units. Dairy cattle decrease and beef cattle increase in relative importance from north to south. The exception to this statement to be noted in the corn sections of the Grazing-forage crop belt and of the Arid Areas (see table II) is occasioned by the irrigated districts of the South Platte Valley. The intensive cultivation and the abundant feed in these irrigated districts, especially alfalfa and beet pulp, favor the development of dairying But even in these irrigated districts beef cattle are more important than dairy cattle.

Many of the cattle raised on the Great Plains are sent to the Corn belt for fattening, often for further growth also. Such cattle are known as feeders and stockers. Corn is abundant and cheap in the corn belt, whereas pasture is abundant and cheap on the Plains, and pasture is especially adapted to growing stock. Thus these two regions supplement each other, and contribute considerably over half of the beef consumed in the United States. The Great Plains region had, on January 1, 1920, over one-third of the beef cattle in the United States (Fig. 13).

Dairying is slowly developing in the Great Plains region, particularly in the moister Black-Earth belt, and in the spring wheat section of this belt it seems not unlikely that it will eventually replace wheat as the leading farm enterprise (Fig. 14). At a few places in the Farming-grazing belt dairying has also been successful, but in this belt, and especially in the Grazing-forage crop belt, the large acreage of pasture required to carry a cow makes dairying difficult except as a minor farm enterprise.

Horses and Mules.—Horses are raised and used throughout the Great Plains for farm power and transport purposes. A considerable number of colts also are raised, especially in the Northern Plains, for shipment to the eastern horse markets. Horses, like beef cattle, can be raised perhaps more cheaply on the pasture of the Great Plains than anywhere else in the United States (Fig. 15).

Horses are needed in the cropped portions of the Great Plains for plowing, seeding, and harvesting, and in the grazing belts for the ranchers and cowboys to ride; hence, horses are more evenly dis-

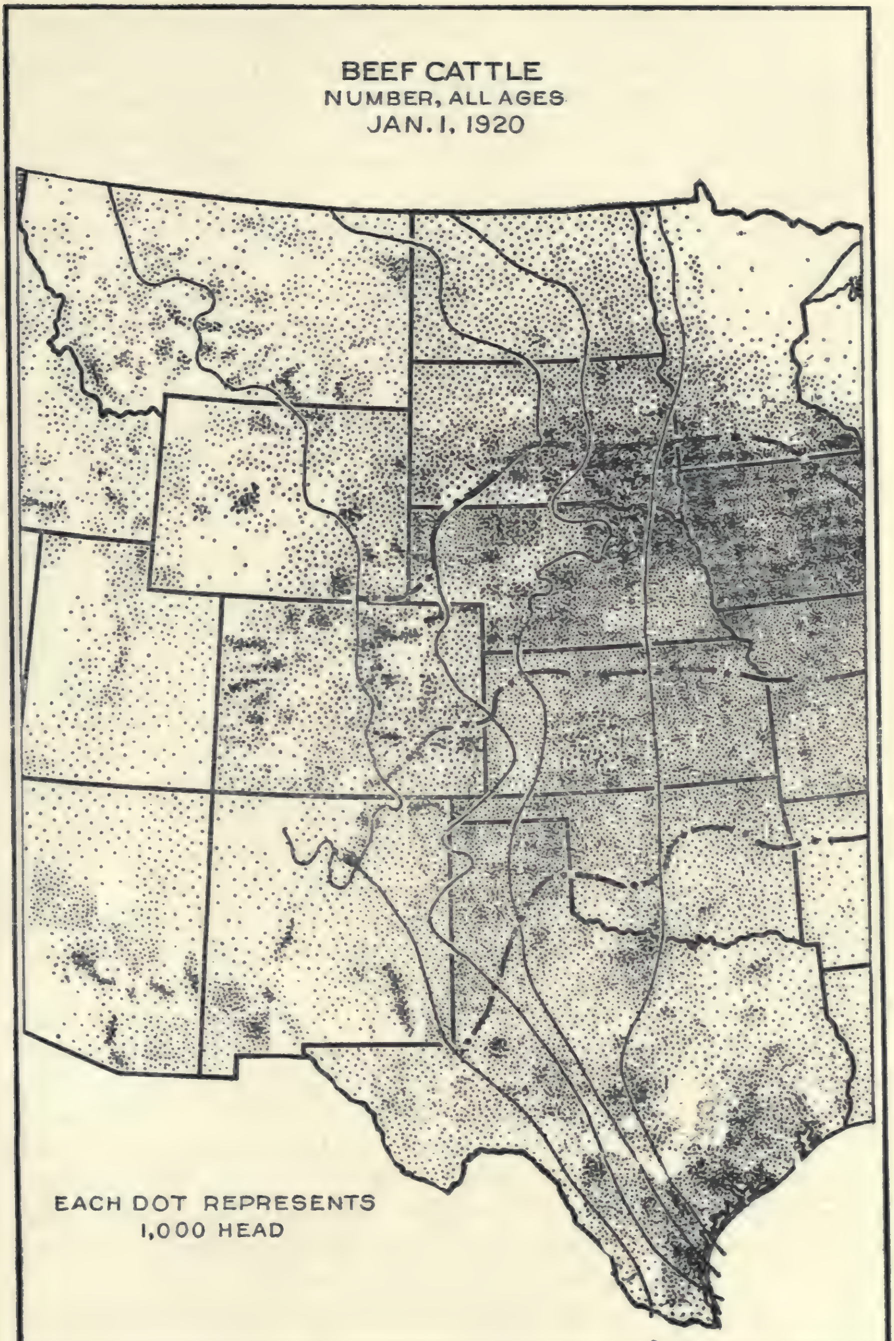


FIG. 13.—Distribution of Beef Cattle.

tributed over the plains than any other class of livestock. In the Southern Plains mules are almost as numerous as horses, but in the Northern Plains there are very few mules (Fig. 15). Horses and mules constitute nearly one-fourth of the total animal units in this region, nowhere exceeding one-third nor falling below one-tenth, except in the cotton section of the arid areas.

Sheep.—Sheep raising is locally an important industry in the Great Plains. Most of the sheep are located in the arid districts along the Milk, Missouri, Musselshell and Yellowstone rivers in Montana, along the Little Missouri breaks and other rough lands in northwestern South Dakota, on the poorer semi-arid lands of northeastern Wyoming, in the North and South Platte Valleys of southeastern Wyoming and northeastern Colorado, in the Pecos Valley of New Mexico, and on the Edwards Plateau of Texas (Fig. 15). Because of their cleft lip, sheep can graze shorter grass than cattle, and needing less water, are better adapted than cattle to arid lands.

It is interesting to note that sheep constitute 1.5 per cent of the total annual units in the Black-Earth belt, 2.9 per cent in the Farming-grazing belt, 9 per cent in the Grazing-forage crop belt, and over 12 per cent in the Arid and Badlands areas. The sheep, except in Texas, are usually handled in flocks of 1000 to 1500, in charge of a shepherd, and roam across these arid or semi-arid lands ever seeking fresh pastures. In that portion of the Plains adjacent to the Rocky Mountains, most of the sheep graze in the summer in the National Forests, usually above timber line, and before the first snows are brought down into the valleys or deserts for the winter. In Texas, where most of the land has been in private ownership for years, much of the range is fenced with wolf proof wire. Allowing the sheep to graze freely avoids much of the tramping of the vegetation by the moving flock and almost doubles the carrying capacity of the range.

If the present price of wool continues it seems not unlikely that the sheep industry in the West will expand considerably. The world's population is increasing at the rate of about 20 million a year and the waste lands are being occupied. As the world fills up with people it seems almost inevitable that the price of both wool and meat will rise, and as sheep supply mutton as well as wool, the future of the sheep industry in the western states seems assured. Moreover, as the United States imports a large part of the wool it consumes, the prosperity of the industry can be facilitated by import tariffs.

Hogs.—Hogs are of importance only in the Black-Earth belt, and in this belt are of great significance only in eastern South Dakota and Nebraska, and in northern Kansas, in other words, only in that portion

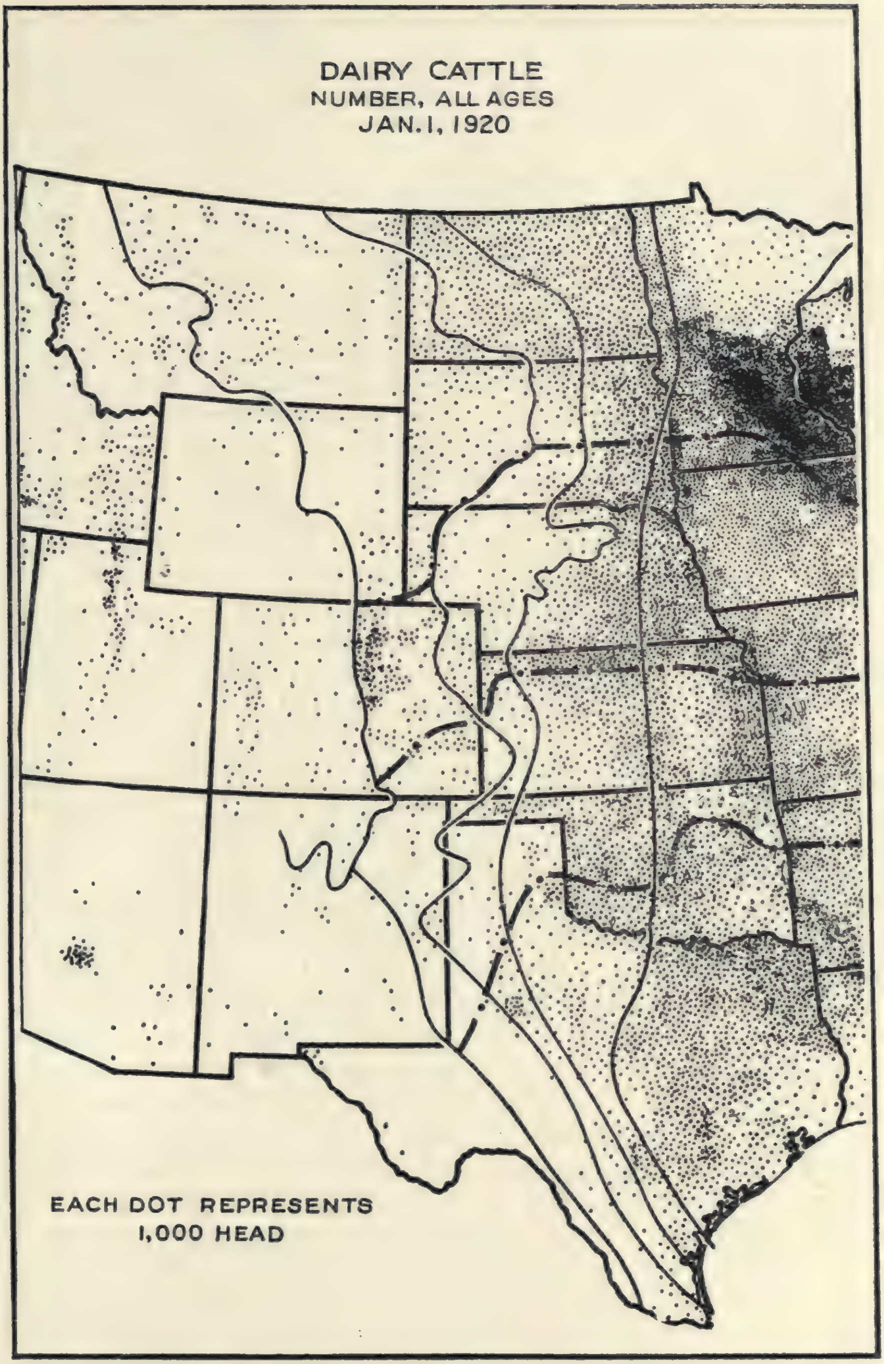


FIG. 14.—Distribution of Dairy Cattle.

of this belt where corn is the dominant crop (Figs. 8 and 15). They constitute about 15 per cent of the total animal units in this corn section of the Black-Earth belt, and 8 per cent in the Black-Earth belt as a whole, whereas in the Farming-grazing belt they constitute 4.1 per cent of the animal units, in the Grazing-forage crop belt 1.9 per cent and in the Arid and Badland areas 1.5 per cent. Hogs require concentrated feed, such as grain and alfalfa, and would starve on short grass pasture on which cattle thrive. Hogs, therefore, are produced in the semi-arid belts outside the irrigated districts only in small numbers and mostly for home use. For this purpose two or three hogs, fed in part on refuse grain, can often be kept with profit, primarily because the farmer can save paying the consumer's price for meat, which is frequently two or three times the producer's price.

AGRICULTURAL PRODUCTIVITY.—Statistics of average value of agricultural products per acre are not available for a series of years, but Fig. 16 presents a rough approximation to such figures. It is based on the value of the crops produced in 1919 plus one-fourth the value of the live stock on January 1, 1920. The year 1919 was one of the driest ever known in North Dakota and Montana; hence, this map does injustice to these states. A similar map for 1909 is provided, therefore, even though it also fails to do justice to the western Dakotas and Montana, since settlement of the dry-farming lands had scarcely begun at that time.

Productivity of the Moisture Belts.— Along the eastern boundary of the Black-Earth belt the average gross value of agricultural products per acre of land area ranged in 1919 from about $25 in southeastern South Dakota and northeastern Nebraska to about $10 in Texas, where much of the land is too rough for crop production. In North Dakota and Texas the western boundary of the Black-Earth belt corresponds rather closely with the $7.00 per acre productivity line, but in South Dakota, Nebraska, and northern Kansas, it is close to the $10 per acre line. This discrepancy is due in large measure to the exceptionally dry season in North Dakota, and in Texas to the fact that the western boundary of the Black-Earth belt is drawn without regard to local topographic conditions. The eastward dip of the $10 line in the southern portion of the Texas Panhandle and along the Kansas-Oklahoma boundary, is owing almost wholly to large areas of rough topography, which preclude in part the cultivation of crops.

The western boundary of the Farming-grazing belt similarly follows quite closely, except in northeastern Colorado, the line of $2.00 per acre productivity in 1919; and the western boundary of the Grazing-forage crop corresponds in general to the line of $1.00 per acre productivity.

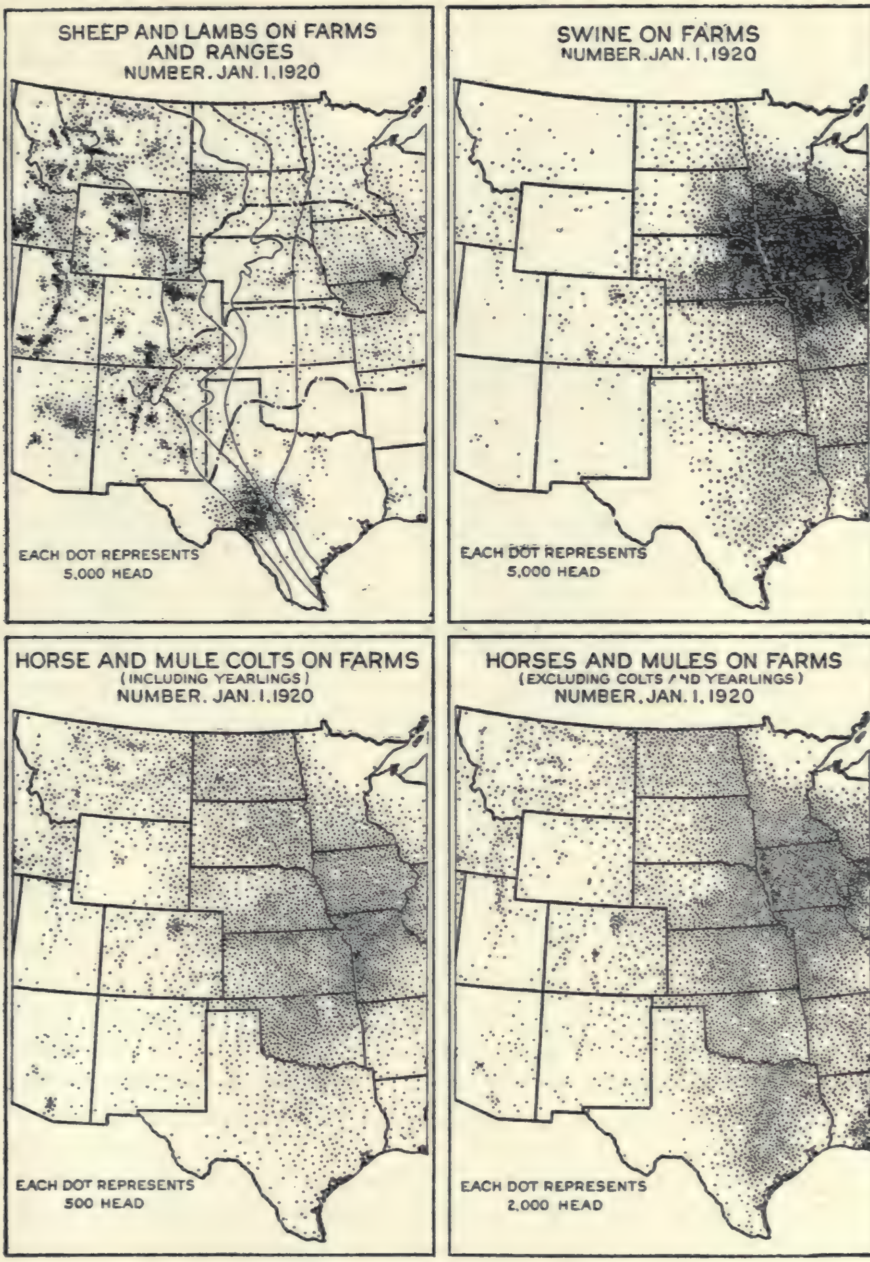


FIG. 15.—Distribution of Sheep, Swine, Horses and Mules.

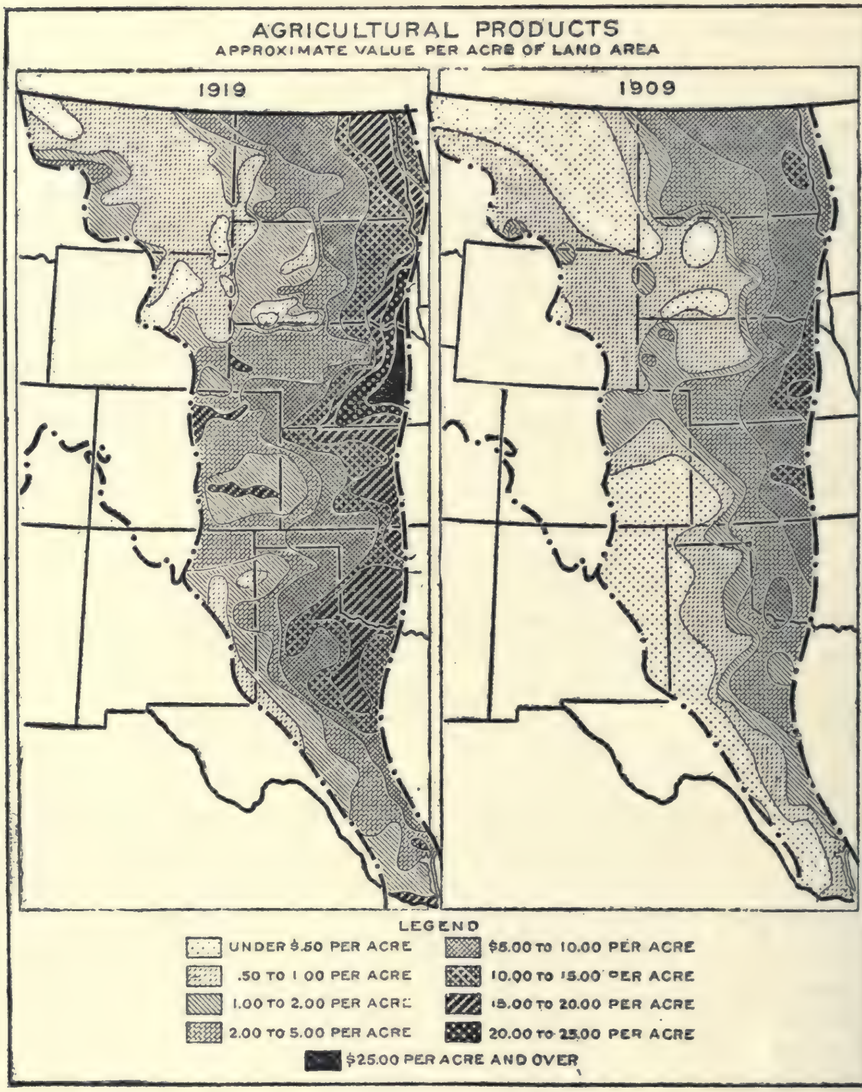


FIG. 16.—Value of Agricultural Products Per Acre 1909 and 1919.

The arid areas have values of agricultural products of less than $1.00 per acre, except where partly irrigated, as in the Arkansas and South Platte valleys of Colorado, in which case the average productivity rises to over $15 per acre. The lowest productivity—less than 50 cents per acre—is found in that portion of the central Wyoming desert included within the Great Plains, and in the driest section of north central Montana, around Shelby and Chester. Fifty

cents, however, is an abnormally low productivity for this Montana district; one to two dollars is probably about normal. Much of the land in the vicinity of these towns was plowed and seeded during the wet years 1914, 1915 and 1916. The yields were high and improved farms sold for $30 and even $40 an acre. Yet climatic records show an average annual precipitation of only 12 and 10 inches, respectively. In 1919 almost any of this land could have been bought for $10 an acre. Towns, schools, roads, many of the farm buildings, —in brief, the entire system of civilization, achieved mostly on borrowed capital, has been built upon a $5 to $10 per acre instead of a $1.00 to $2.00 per acre gross productivity.

The notable increase in value of agricultural products per acre between 1909 and 1919 should be noted. This, of course, is owing in large part to the much higher prices of agricultural products in 1919, but also in part to progress in agricultural development. The $5.00 per acre productivity line followed closely in 1909 the western boundary of the Black-Earth belt across the Dakotas and Nebraska; but in the southern plains the productivity per acre along this western boundary of the Black-Earth belt was only about $1.00 per acre. The gross productivity of the land along this boundary in the northern plains, therefore, about doubled during the decade, as measured in dollars; whereas, in the southern plains it increased, on the average, about five-fold.

Factors Affecting Productivity.—Although the climatic, topographic and soil conditions are the primary factors in determining the productivity of land in the Great Plains region, scarcely less important at present are distance from railroad and good public highways. The writer recalls in a recent auto trip across the level plains of western Kansas that distance from a railroad station could be estimated closely by noting the proportion of the land in crops. Six or seven miles from a town all the land was usually in native pasture. At about five miles an occasional field of wheat appeared, at four miles perhaps one-fourth of the land was in wheat, corn, or grain sorghum, at two miles apparently about half the land was in crops, and close to town nearly all the land.

Apparently, the cost of hauling wheat to the elevator was such that at the prices prevailing it did not pay, under the semi-arid conditions in this district, to raise wheat more than six or seven miles from a railroad. As the roads improve this distance will doubtless increase. A sharp rise in the price of wheat would have the same effect, and would cause the breaking up and seeding to wheat of thousands of acres of pasture land. Also, where the rain fall is heavier and the acre-yield

higher, it pays to haul wheat a greater distance, other factors remaining equal. Much of the wheat in the Farming-grazing belt is grown ten to fifteen miles from an elevator. Cases are known to the writer in which wheat has been hauled 60 miles to a railroad.

Figure 17 shows the areas of land in the Great Plains distant more than 5 miles, more than 15 miles, and more than 25 miles from a railroad. It will be noted that along the eastern edge of the Black-Earth belt most of the land is within five miles of a railroad, whereas in the Grazing-forage crop belt there are several large areas of land which are more than 25 miles from a railroad.

Size of Farms.—Throughout the Great Plains, as in all parts of the United States, the trend is toward the family size farm. No corporate or other form of large-scale agricultural operations can compete permanently, it would appear, with the individual farmer, who knows nothing of 8-hour days, possesses the stimulus afforded by private initiative, and works for a much smaller compensation than that received by urban labor.

Value of Products, not Acreage, the Measure of Size.—The size of farms in the Great Plains, even more than in most parts of the United States, must be measured by productivity and not by acreage. Farm surveys in Nebraska have shown that 640 acres, or one section of land, in the western portion of the state yield products of no greater value, on the average, than 160 acres, a quarter section, in eastern Nebraska. In 1919 the average gross value of products per farm (value of crops plus one-fourth value of live stock) was about $4,000 in both eastern and western Nebraska. In many of the counties of Montana, which contain both live stock ranches and dry land farms, the gross productivity per farm in this dry year averaged less than $500, the lowest, in Liberty County, being only about $200. In Sutton County, Texas, on the other hand, where the farms (ranches) average over 8,000 acres in area, the gross value of products in 1919 was about $12,000 per farm. These are the extremes, the average in this year in well-settled farming communities being about $4,000 to $5,000, and the tendency is toward a farm area yielding products of this gross value. This means 5,000 to 6,000 acres of land at 80 cents per acre productivity, such as is found along the arid margin of the Grazing-forage crop belt, or 500 to 600 acres of 8 dollar productivity land, which acreage and productivity characterized the semi-arid margin of the Black-Earth belt. With normal prices of farm products and normal costs of production the gross value of products per farm and per acre would probably be only about two-thirds this amount. The important fact to note is that the size of the farm in the Great Plains

FIG. 17.—Distance from Railroad in Great Plains.

especially must be measured on the basis of value of products per farm, not of acreage. In no agricultural region in the United States is there greater range in productivity per acre than in the Great Plains.

Changes in Size of Farms.—The increase in acreage of farms, due principally to decreasing precipitation westward, is indicated in Fig. 18, in which three lines have been drawn, one through those counties where the average total acreage of land per farm is about 320 acres, one where it is about 640 acres, and one where it is about 1280 acres. In the Gulf Coastal Plain area these lines are only about 25 miles apart, which is closer than the natural conditions justify. The westward movement of crop farming into this area has been retarded by the ownership of the land by wealthy cattlemen, but the ranches are now being broken up and sold off in family sized parcels. Another census will probably show a movement westward of the 640 and 1280 acre lines in the area.

In central Kansas, where it has been 40 years since the land was homesteaded and agriculture has had ample time to adjust itself to the physical conditions, the lines are only about 75 miles apart, and are permanent, the shifting back and forth, as shown by the last four census returns, being seldom greater than the width of a county. The 320-acre size line in this winter wheat section corresponds roughly with $15 productivity per acre in 1919 and 25 inches average annual precipitation, the 640-acre size line with $7.50 per acre productivity and 20 inches precipitation. No county in Kansas has farms averaging as large as 1280 acres, but in the Texas Panhandle and in northwestern Nebraska where such county averages are found, the productivity ranges in general between $3 and $4 per acre. The average annual precipitation in northwestern Nebraska is about 16 inches, and in the portion of the Texas Panhandle considered it is about 18 inches. The size of farms across central and western Kansas increases about 3 1/3 acres per mile, while the productivity per acre in 1919 decreased about 8 cents per mile, and the average annual precipitation 1/16 to 1/20 inch per mile.

In North Dakota and Montana the zones between the acre-size farm lines spread out fan-like, the 640-acre line along the Canadian boundary being nearly 400 miles west of the 320-acre line, and the 1280-acre line about 100 miles further west. This divergence is noteworthy also on the productivity map, and is due to a less abrupt diminution of rainfall than further south. This belt between the 320 and 1280 lines of average acreage per farm covers much of the area of uncertain crop production. Its greater width in the spring wheat section of the Great Plains means that a larger area is here subject to the vicissitudes of

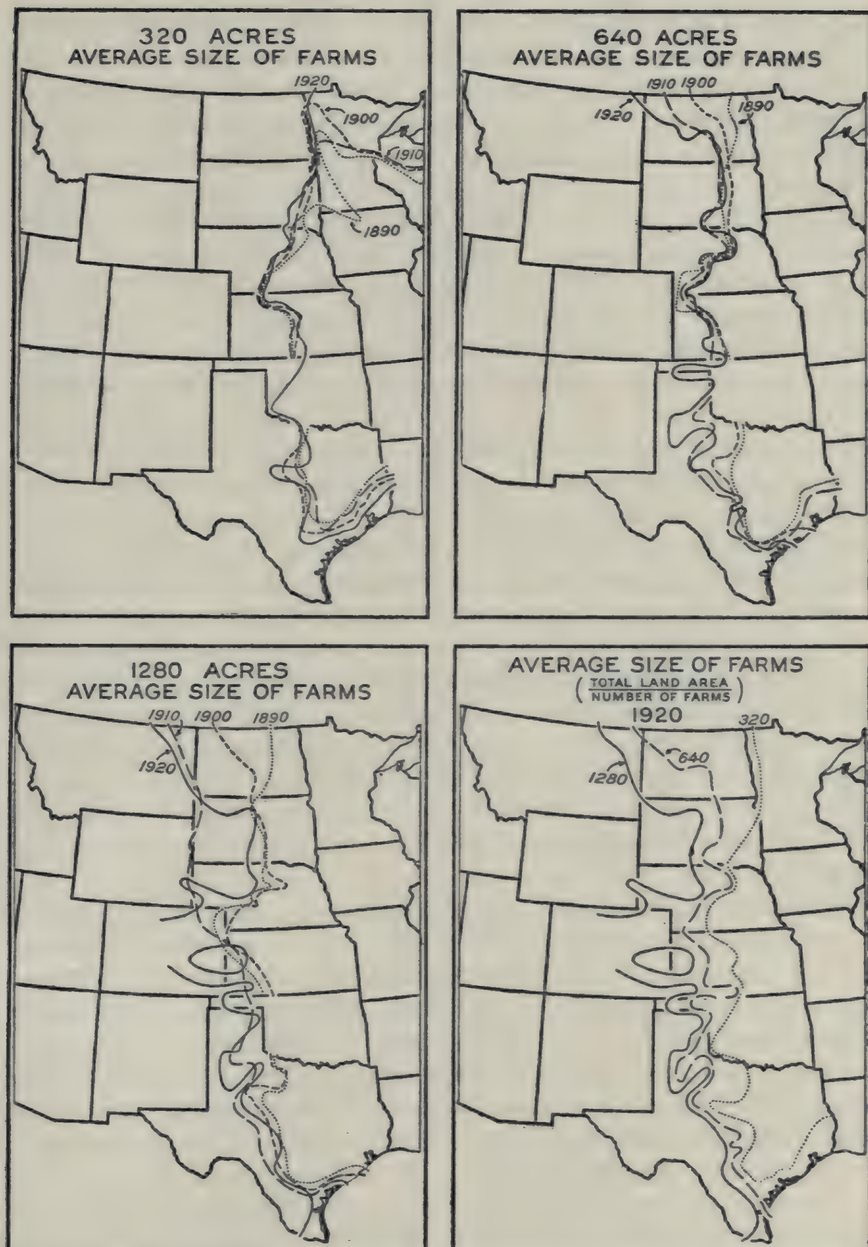


FIG. 18.—Changes in Average Area of Farms 1890-1920.

rainfall, and consequently that a larger number of farmers are involved in the alternating periods of prosperity and adversity.

It is interesting to note that in the Dakotas and Montana where this belt spreads out to a width of several hundred miles, there has developed out of the economic distress serious political dissatisfaction. In Nebraska, owing in large part to the Sand Hills, this belt of marginal crop land is very narrow; and in Kansas, as already noted, the 320, 640 and 1280 acre lines are only about 75 miles apart. Possibly there are not enough farmers in this belt of economic vicissitudes to make their influence felt politically in these states. Or it may be that the political peacefulness in Nebraska and Kansas is owing to the longer time since settlement and the accumulation of agricultural experience and capital. The existence of the Populist Party in these states some 40 years ago, which was a movement similar to the present movement in the spring wheat section, suggests that this greater accumulation of capital is, at least, a partial explanation.

Probably the greatest agricultural problem in the Great Plains region, more especially in the Farming-grazing and Grazing-forage crop belts, is the reorganization of the ownership of the land into units neither too small nor much too large for the support of a family according to the American standard of living. In Montana this will mean mostly consolidation of homestead holdings; whereas in parts of Texas it will involve division of large live-stock ranches. The area of these ultimate farm units will vary with the physical conditions, the distance from a railroad, and the capacity of the farmer, but will tend to approximate a gross production per farm equivalent to $4,000 to $5,000 in 1919.

Systems of Farming in the Great Plains.—With such a diversity of physical conditions as the Great Plains possess—from sub-tropical in southern Texas, where palms and bananas are grown for ornament and citrus orchards expectantly for profit, to sub-polar on the high plains beneath the mountains in northwestern Montana, where frosts occur in every month and no crops, except hay, are grown; from humid conditions along the eastern boundary to desert conditions in some of the valleys of the western portion—it is evident that there must be unusual variety in the systems of farming.

Black-Earth Belt.—Wheat farming is the simplest and also the most important system of farming in this belt. In both the spring wheat section in the Dakotas and the winter wheat section of western Kansas and Oklahoma and northern half of Texas, the farmers grow wheat as the cash crop and usually raise only enough oats to feed their horses, needed in seeding and harvesting the wheat, enough hay for a few

cattle to provide the household with milk and increase the income by the occasional sale of a steer, and enough corn in the northern areas, or sorghum in the southern, to supplement or supplant the hay.

In this system of wheat farming the seasonal distribution of labor is very uneven and unsatisfactory. In the spring wheat section especially peak loads come in the spring at plowing and seeding time and again at harvest time in the late summer and early autumn. Transient labor must be employed at high wages. During the winter, on the other hand, the farmer who grows little else than wheat has little to do. Obviously, a man who works only half the year cannot expect to make as much as one who works all the year. Hence, the trend toward diversification, especially the development of dairying in the spring wheat section and of cattle production in the winter wheat section, both of which systems of farming provide more work during the winter.

Moreover, the exclusive wheat farmer puts all his eggs in one basket, and the price is not determined by the millers in Minneapolis, as he sometimes thinks, but principally by world conditions as reflected in the Liverpool market. The present serious situation in the spring wheat section is due largely to the fact that wheat is a world crop, and the buying power of Europe is greatly reduced, while the production of wheat in many countries, Canada especially, has greatly increased. A campaign for diversification is in progress in the area, similar to the campaign for diversification during recent years in the South; and although the change in systems of farming will come slowly, it is probable that in the course of time western Minnesota and the Black-earth portions of the Dakotas will develop, like Eastern Minnesota and Wisconsin, into dominantly dairying districts. In 1920 over two-thirds of the farms in North Dakota had dairy cattle, these farms averaging seven dairy cows per farm, which is over double the average number in 1910.

The ultimate system of farming in the winter wheat districts of central Kansas and western Oklahoma is less clear, but probably it will be a more diversified system even than dairying, and one in which wheat, corn or kafir, and beef cattle will be the leading enterprises—a system similar to that in the southern portion of the Corn Belt.

In the Corn Belt section of this Black-Earth belt the present system of farming, based largely on corn, cattle, and hogs will doubtless continue dominant. Wheat, oats and hay are important crops in this section and probably will remain so. The system of agriculture in this section is one of the most satisfactory in the United States, and little change seems likely to occur.

In the Cotton Belt section of the Black-Earth belt a ten fold increase in wheat acreage, a three fold increase in the grain sorghums, and a two fold increase in cotton acreage occurred between 1909 and 1919, whereas the corn acreage diminished somewhat. Owing to the diverse topographic and soil conditions, there are several systems of farming in this section, and these will doubtless continue, but with increasing emphasis, probably, on cotton, because of the freedom from the boll weevil of large areas in this section. Crop systems of farming seem likely to continue encroaching upon livestock ranching, more particularly in the Staked Plains and Gulf Coast areas.

The Farming-grazing Belt.—In this belt it appears likely that the present major systems of agriculture will continue. These may be grouped into three general types:—(1) grain farming, (2) mixed grain and livestock farming, and (3) livestock ranching. The methods of grain farming will probably become more extensive in order to reduce the costs of production. The use of eight and even twelve horse rigs or traction outfits in plowing and seeding is likely to become more common, permitting the cultivation of a larger acreage per farm. In the mixed grain and livestock farming, live stock will be the chief dependence, the grain being grown on the more level land in the farm and the live stock grazed on the rougher or hilly land, also on the sand hills where the sand is not underlain with a heavier soil. Shallow sandy soils in this belt have proven to be the safest forage crop soils (corn and the sorghums), especially from southwestern Nebraska southward to Texas. The livestock ranching will be confined largely to the gravelly moraines, belts of badlands, and the sand hill areas, notably in Nebraska.

Cattle are at present the most important kind of live stock in this belt, and natural conditions suggest that they will always remain so. The system of cattle farming, however, will change, indeed, has changed. It has become sedentary with the passing of the land into private ownership and the fencing of the range, and will become more intensive as capital accumulates, prices of beef rise, and the importance of producing enough forage on the ranch to keep the cattle through the winter becomes more pressing. If the American standard of living is to be maintained, the farm or ranch must be big enough to carry about 100 head of cattle, which will mean, in general, from one to two sections of land (640 to 1280 acres), depending upon the carrying capacity of the range. In such livestock farms one or two hundred acres of the level land may be put in wheat, and about an equal amount in corn or sorghums for winter feed. Slowly the large ranches will be divided, as many have been in the past, and the small farms, on

the other hand, consolidated into units of this size. Not all the large ranches will be divided, however, nor all the small farms consolidated, because there are as great differences in men as in land. Every community needs one or more big farmers who have the capital to buy and introduce pure-bred stock, undertake experiments in methods of production, and serve in general as agricultural leaders of the community.

The Grazing-forage Belt.—In this belt, the annual value of the grazing exceeds the value of the crops, and the agriculture becomes dominantly pastoral. There is and probably will continue to be, however, the same three major types of farming as are found in the Farming-grazing belt to the east, but the grain farming system seems likely to become even less common and the livestock system more important. The grain farms are much the same size as in the belt to the east, because a section of land is all that a family can handle, even with the most efficient farm machinery. The live stock farms are larger than in the moister belt because the carrying capacity of the pastures is lower. Two to four sections of land are required, in general, to carry 100 cattle, and in addition most of the cattle ranchers will put in a hundred acres or so of forage for winter feed.*

Arid and "Badlands" Grazing Areas.—Lastly, we come to the arid areas, the sand hills, the "breaks" and "badlands," which occupy in all about 70 million acres in the Great Plains region. Most of the sand hills, the "breaks" and "badlands," and the moister portions of the arid areas are used for grazing cattle; but the herding of sheep, doubtless, will continue to be the principal system of farming in the drier districts. In general, outside of Texas, this is a primitive, migratory system of farming, if such it may be called, in which the shepherd moves about with his flock as he did in David's time. But the arid districts undoubtedly will be fenced in time, and the sheep industry become more sedentary. More than four sections of land will be required, probably, to support a profitable sheep outfit in these driest districts. In the Edwards Plateau area this sedentary system of livestock management is well developed, but includes cattle and goats ranged on the same land with the sheep. In Sutton County in this

* Since this paper was written the bulletin by M. L. Wilson entitled "Dry Farming in the North Central Montana Triangle" has been published, Montana State College Exten. Serv., 66. This noteworthy discussion by the most competent authority on the agriculture of the semi-arid sections of the northern Great Plains, though urging diversification and live stock, still advises wheat as a cash crop for this most arid portion of the northern Plains.

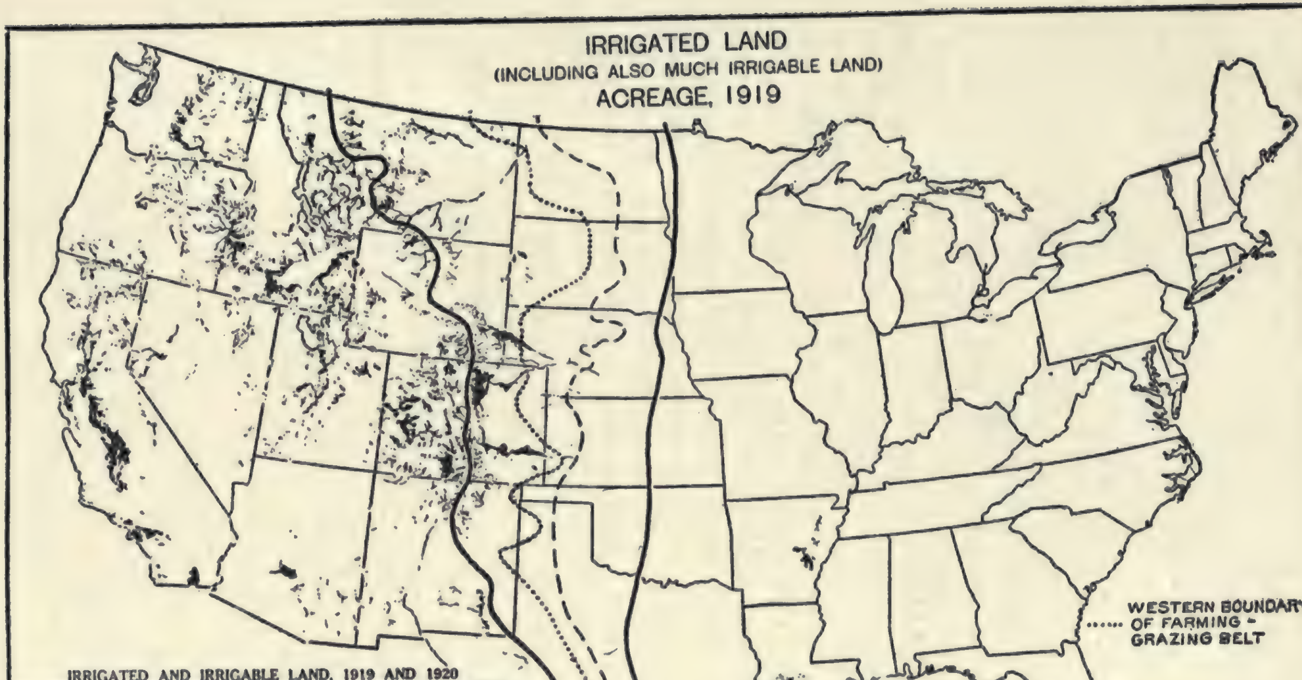
area nearly two-thirds of the farms are between 4 and 20 sections in size.*

The Irrigated Districts.—The agriculture of the irrigated districts, which are located mostly in these arid areas, is important in the Great Plains, and will undoubtedly become more important with the passage of time. It has not been described because it is not characteristic of the Great Plains region. The general system of farming in the irrigated districts, like that along the northern margin of the Corn Belt, is based on some intertilled crop, usually corn or sugar beets, followed by a small grain, usually wheat, and then by hay, commonly alfalfa, which may occupy the land for several years, and be pastured incidentally. Quite commonly both cattle and sheep are brought down off the plains into the irrigated districts during the winter and fed beet pulp or corn fodder, supplemented sometimes with grain. The irrigated lands are a steadying force in the agriculture of the arid and semi-arid portions of the Great Plains region, and often provide school and church facilities that, owing to the sparsity of settlement, the stockmen could not otherwise afford.

THE AGRICULTURAL OUTLOOK.—The farmers and ranchers of the Great Plains region at present are facing a dilemma. The demand for wheat is decreasing, owing to exhaustion of the purchasing power of European peoples, and prices are falling. The demand for cattle is also declining, and prices are below pre-war levels, owing to a change in our national diet involving decreasing consumption of beef. The per capita consumption of beef in the United States dropped from 90 pounds in 1907 to 65 pounds in 1921, and the number of beef cattle in the United States is less than it was 25 years ago.

Wheat and beef are the two most important products which the farmers of the Great Plains, outside the cotton section and arid areas, have to sell to the world. Sheep are important in the arid areas, but have been gradually pressed out of the moister lands by wheat and cattle. In general, the alternative to wheat is beef cattle, and the alternative to beef cattle is sheep. Land which is worth 25 dollars an acre for wheat is normally worth only 5 to 10 dollars an acre for grazing cattle, and 4 to 8 dollars an acre for sheep. A change in system of farming from wheat to beef, therefore, unless the wheat-land be used for feed grains and forage crops, which involves additional capital, generally

*"An Economic Study of a Typical Ranching Area on the Edwards Plateau of Texas," by Youngblood and Cox, Texas Agricultural Experiment Station, Bul. 297, page 109. This notable contribution to Range Economics should be read by all interested in the subject.



IRRIGATED AND IRRIGABLE LAND, 1919 AND 1920

STATE	AREA IRRIGATED, ACRES 1919	AREA ENTERPRISES WERE CAPABLE OF IRRIGATING	AREA IN ENTERPRISES, ACRES 1920	ESTIMATED IRRIGABLE AREA (INCLUDING IRRIGATED)	STATE	AREA IRRIGATED, ACRES 1919	AREA ENTERPRISES WERE CAPABLE OF IRRIGATING	AREA IN ENTERPRISES, ACRES 1920	ESTIMATED IRRIGABLE AREA (INCLUDING IRRIGATED)
Calif. .	4,219,040	5,894,466	7,885,207	10,000,000	Wash .	529,899	637,151	836,795	3,000,000
Colo. . .	3,348,385	3,855,348	5,220,588	5,000,000	Ariz . .	467,565	627,303	813,153	1,000,000
Idaho .	2,488,806	3,092,810	3,780,048	5,500,000	La . . .	454,882	728,742	851,211	. . . . .
Mont. .	1,681,729	2,753,498	4,329,148	6,000,000	Nebr. .	442,690	562,466	766,768	1,000,000
Utah. .	1,371,651	1,700,550	2,359,244	2,500,000	Ark . .	143,946	179,013	246,400	. . . . .
Wyo. .	1,207,982	1,831,039	2,564,668	4,000,000	S Dak	100,682	150,914	188,382	1,000,000
Oreg. .	986,162	1,344,046	1,925,987	3,000,000	Kans. .	47,312	67,853	102,562	500,000
Tex. .	586,120	1,150,542	1,687,447	3,000,000	N Dak	12,072	34,235	57,476	1,500,000
Nev. . .	561,447	704,708	1,382,036	1,500,000	Okla. .	2,969	9,672	11,742	500,000
N. Mex	538,377	696,119	961,879	2,000,000	U. S. . .	19,191,716	26,020,477	35,890,821	51,000,000

Fig. 19.—Acreage of Irrigated Land.

means bankruptcy for the wheat farmer, and from beef to sheep is likely to spell a similar fate for the cattleman.*

Because of these established land values, whose deflation means bankruptcy, as well as because of the smaller area and different organization and equipment of their farms, wheat farmers persist in growing wheat even when the price is far below the cost of production. Similarly cattlemen are slow to shift to sheep. Their ignorance of and dislike for sheep is also a deterring influence. It is easy for farmers to climb the ladder of rising land values from sheep to cattle and cattle to wheat, but deflation means disaster.

Happily the normal trend, owing to increasing population, is toward more intensive use of the land. The present export surplus of wheat, one-fifth to one-quarter of our production, will be required by the increase in population within 20 years; and partial replacement of wheat by other crops in the humid portions of the United States, where half of the enormous increase in wheat acreage between 1909 and 1919 occurred, will shorten materially this period of surplus. In fact, the next season, 1920, other crops were substituted for two-thirds of the 14 million acres increase in wheat acreage in the humid region during the decade, and the acreage is now (1923) nearly back to pre-war levels. In the sub-humid Black-Earth belt, where one-quarter of the increase in wheat acreage between 1909 and 1919 occurred, it is more difficult to replace wheat by other crops because the farm organization and equipment are suited primarily to wheat production; nevertheless, in 1920 other crops were substituted for one-half of the seven and one-half million acres increase in wheat in this belt between 1909 and 1919, and the acreage is now back to the pre-war level. In the semi-arid belts, where one-quarter of the increase in wheat acreage occurred, practically the only alternatives to wheat are forage crops and grazing, and the acreage of wheat has not declined appreciably since 1919. There are about 15 million acres in these semi-arid belts on which the sod has been broken and which, apparently, at the present prices of cattle and forage crops, can be used only for wheat, or left idle.

The prospect for the cattle industry is not reassuring. If in these present times of urban prosperity the demand for beef is insufficient to raise the price above pre-war levels, it does not seem likely to increase during the quieter times which must be expected soon. It may develop, however, that population will increase more rapidly than

* Just at present, the price of wool and lambs is so high (fully double the pre-war price, whereas beef cattle and wheat are practically at pre-war prices) that sheep are pressing in upon the cattle range.

per capita consumption decreases, in which case the price of beef and the prosperity of the industry will improve.

Thus to the inexperience of many farmers in the systems of agriculture adapted to the varying physical conditions in the Great Plains, and to deficiency of capital which characterizes all pioneer regions, there have been added recently two more obstacles to agricultural progress, an appalling decline in the price of wheat and a price for beef which remains stationary at pre-war levels. The Great Plains region presents the most pressing problems in American agriculture, and deserves all the help which national and state agencies for the promotion of agriculture can offer.

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THE LAWS OF WINDS AND MOISTURE*

STEPHEN SARGENT VISHER

CONTENTS

LAWS CONCERNING WINDS

KINDS OF WINDS.

27. *There are three great kinds of winds:* (1) *planetary,* (2) *continental,* and (3) *cyclonic.*—The first are due chiefly to latitudinal differences in insolation; the second to differences in heating and cooling of land and water. Cyclonic winds are due in part to other causes, not well understood. Minor winds include mountain and valley breezes and winds associated with tides, land slides, earthquakes and explosions.[82]

DIRECTION OF WINDS.—*Effects of Temperature Differences.*

28. *Surface winds commonly blow from colder areas to neighboring warmer areas because warm areas usually have lower air pressure than nearby cooler areas, and winds blow from places of higher air pressure to places of lower air pressure, though at a small angle to the isobars where friction is slight.*—Great insolation along the heat equator gives

* Laws of Temperature were presented in the March, 1923, number of the ANNALS, pp. 15-40.

[82] Shaw, W. N.: Principia Atmospherica, Laws of Atmospheric Motion, *Mo. Weather Rev.,* Vol. 42, pp. 196-209, 1914.

rise to persistent winds (the planetary circulation). Other more local winds, due indirectly to differences in air temperatures, are land and sea breezes,[83] monsoons, and valley and mountain breezes. There are two exceptions to this general rule. If an area is excessively heated for a very short time, only the flow of air away from the heated area has time to take place.* Furthermore, with every mid-latitude cyclonic storm, part of the wind comes from warmer areas.

29. *A great system of winds (the planetary circulation) results from the combined influence of intense equatorial heating and of the earth's rapid rotation.*—Intense insolation produces low pressure along the thermal equator.[84] The deflective effects of the rotation of the earth produces low pressures in high latitudes (lowest about 60° instead of near the poles largely because of the chilling influence of the snow caps).[85] Between the equatorial and subpolar belts of lower pressure, a belt of relatively high pressure occurs near the margin of the tropics (averaging about 35° N. and 30° S., but shifting with the seasons). From the barometrically higher parts of this high pressure belt, winds blow toward the equator (the Trades) and toward the poles (the Westerlies in part). These higher centers of the Belt of Highs lie over the ocean because of the comparatively low temperature there, caused in part by the upwelling of cold waters.[86] The Horse Latitude Highs are maintained by the Anti-trades supplemented by the centrifugal force between the eastward blowing Westerlies and westward blowing Trades.†

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[83] Ward, R. De C., Land and Sea Breezes, *Mo. Weather Rev.*, Vol. 42, pp. 274-277, 1914.

* See Law 32, beyond.

[84] Blair, W. R., The Planetary System of Convection, *Mo. Weather Rev.*, Vol. 44, pp. 186-196, 1916.

[85] Shaw, W. N., loc. cit. pp. 208, 209.

[86] McEwen, G. F., Peculiarities of the Californian Climate, *Mo. Weather Rev.*, Vol. 42, pp. 14-23, 1914. Humphreys, however, believes that friction is the chief factor.

† The importance of the planetary circulation is so great that it seems worth while to supplement the foregoing simple statement with a fuller one which presents the causes in another way. This statement is based on one kindly contributed by C. F. Brooks.

The great heating of the air in the tropics results in a greater expansion there than in any other belt. The consequent raising of the layers of air especially over the heat equator causes a poleward overflow. Before reaching many degrees of latitude from the equator the deflective effects of the earth's rotation begins to affect this overflow until by the time latitude 30 or 35 is reached the poleward flow is largely arrested, by being converted into an eastward movement. The flow of air from the equatorial regions and its concentration at latitudes 30-35 N. and S.

30. *Appreciable local differences in the heating or cooling of the earth's surface often deflect general surface winds.* Cool areas such as snow-fields and lakes in summer often divert surface winds because such places commonly have a comparatively high air pressure, and hence tend to have outblowing winds.[87] Winds also sometimes change their direction during the day, blowing toward the area of greatest insolation.[88] Likewise lake and sea breezes often shift conspicuously, chiefly because of the deflective effects of the earth's rotation, but partly because of the hourly changes in the area of greatest heating.[89]

31. *Winds are deflected by the rotation of the earth, to the right in the northern hemisphere and to the left in the southern.* (Ferrel's Law.)[90] The deflective effect of the earth's rotation increases as the sine of the latitude from nil at the equator to a strong effect near the

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makes a low pressure belt in low latitudes and high pressure belts on either side, at the earth's surface. The low pressure belt is developed most strongly over the lands, where the expansion due to heating is greatest, and the high pressure belts are best developed over the oceans where the coolness allows a greater compactness of air than is possible over the hotter lands. In high latitudes the cooling over the polar ice-caps contracts the air and allows an inflow from the surrounding regions. In high latitudes, however, the defective effects of the earth's rotation are so great that such inflow can come from but limited distances. The result is the development, at the surface, of high pressures over the polar ice caps, and of broken rings of low pressure at latitudes 60 to 65. Here as in low latitudes the lowest pressures develop over the warmest portion for the latitude (here the ocean in winter, the land in summer), and the highest pressures over the coldest portion, the reverse. The surface winds induced by these belts of pressure tend to modify them by centrifugal action, which in the case of the westerly winds of middle latitudes intensifies the subpolar low pressure belts and the horse latitude high pressure belts, particularly over the oceans, where the slight friction favors strong winds. (The deflective effect of the earth's rotation, per se, cannot modify the wind velocities, and therefore cannot modify gradients. It does, however, prevent the winds from obliterating gradients rapidly by direct flow. Centrifugal action, however, on curved wind paths can increase the gradient of pressure, and thus increase the wind.) Middle and high latitude lands in winter and intermediate and low latitude lands in summer, acting by themselves in cooling or heating the air, produce on a smaller scale the changes and circulation characteristic of the planet as a whole, and being superimposed on these worldwide changes, greatly complicate the distribution of pressure and the resulting winds.

87 Henry, A. J., The Winds of the Lake Region, *Mo. Weather Rev.*, Vol. 35, pp. 516-520, 1907, and Davis, T. H., Direction of Local Winds as Affected by Contiguous Areas of Land and Water, Ibid, Vol. 34, pp. 410-413, 1906.

88 Pernter, J. M., Causes of Diurnal Changes in Wind, *Mo. Weather Rev.*, Vol. 42, p. 661, 1914.

89 Humphreys, W. J., in National Research Council, Introductory Meteorology, p. 106, 1918.

90 Ferrel, Wm., A Popular Treatise on the Winds, 1890.

poles.[91] As a result of this deflective effect the Trades are easterly instead of north or south winds, and the planetary winds of mid-latitudes are westerly, instead of north or south winds. Land and sea breezes "veer" notably in the northern hemisphere and "back" in the southern chiefly because of this deflective effect. The direction of the winds about Lows and Highs and in tropical cyclones also complies with Ferrel's Law.

Effects of Topography.

32. *The prevailing wind direction is peculiar at many points, especially in rugged regions, because surface wind directions are influenced by topographic features.*—Mountain ranges and lesser elevations frequently divert winds, for winds tend to descend valleys and other slopes,[92] because gravity interferes with ascent but facilitates descent. For the same reason wherever slopes are ascended by general winds, valleys are often followed conspicuously.[93]

Seasonal Changes in Direction.

33. *A seasonal change in average wind direction is common.* Changes are produced in three ways: (1) By the seasonal migration of the wind belts, (2) by the development of typical monsoons, (3) by the frequent deflection of the planetary winds caused by high and low pressures produced by unequal heating and cooling of continent and ocean. Many subtropical areas are within the Trade Wind belt in summer and within the Westerly wind belt in winter. Other subtropical or warm temperate areas have land monsoons in winter and ocean monsoons in summer. Farther north, in the northern hemisphere, there is likewise a seasonal change in average wind direction due to changes in average barometric pressure. Continents commonly have high average pressures in winter and low average pressures in summer. Thus there is a strong tendency for barometric minima to develop over oceans in winter. Hence southerly or westerly winds predominate in winter on western coasts, and northwesterly winds on eastern coasts. For example, southwest winds predominate in winter in western Europe and in western North America, north of California, while northwest winds prevail in eastern North America and in eastern Asia.

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[91] For table showing radius of curvature of deflection for different latitudes see Davis, W. M., Elementary Meteorology, p. 104, or Milham, W. I., Meteorology, p. 161.

[92] Day, P. C., Winds of the U. S., *Yearbook of the Dep't of Agriculture for* 1911, p. 340, and Henry, A. J., Climatology of the U. S., *Bull. Q., U. S. Weather Bureau*, pp. 67-75, 1906.

[93] Davis, W. M., Elementary Meteorology, p. 98, Figs. 29, 30; 1894.

Conversely, in summer low pressure over the drier parts of the continent commonly give rise to southerly winds on the eastern side of the continents, and northwesterly winds on the western side. For example, the average wind direction in summer for the eastern half of the United States, is from the southwest or south and that of eastern Asia from the southeast, while at the same time western Europe and western United States are having northwesterly winds.[94]

Changes with Altitude.

34. *Wind direction aloft is different from that nearer the surface usually being more to the right of the surface direction* (in the northern hemisphere). At higher and higher elevations up to a height of about 2,000 feet (610 m.) the wind makes a progressively greater angle with the line representing the steepest gradient, that is, they blow at a smaller angle with the isobars. This is because with decrease in friction the flow of air with a given gradient is more rapid, and therefore the deflection is greater, thus bringing the wind direction more nearly parallel to the isobars. At even higher elevations, where friction is only slightly less, wind direction continues to change, becoming progressively more nearly parallel with the isobars, which at high altitudes seldom depart more than 30° from an east-west direction. This change is because of the increase in centrifugal force which accompanies increased velocity, and occurs in spite of the fact that the decrease in the earth's rotational deflective effects, which accompanies the increase in wind velocity with altitude, tends to make the wind direction less nearly parallel to the isobars. The weakening of the pull of gravity permits the centrifugal tendency to overcome the tendency to turn to the right (northern hemisphere).[95]

Diurnal Changes.

35. *Surface winds at low altitudes often "veer" during the day and "back" at night. At higher altitudes the diurnal shifting is commonly in the opposite direction.*—A diurnal change of 12° in wind direction is common. This shifting is due largely to convectional inter-

[94] Hann, loc. cit., pp. 172-178, gives several tables showing average monthly wind directions for stations in Europe, Asia, and North America. He also states that continents resemble cyclones in summer and anticyclones in winter. Köppen's charts for normal wind directions on the ocean for July-August and Jan.-Feb. are reproduced in Moore's Descriptive Meteorology and in Humphreys, Physics of the Air. See also Ward R. De C., The Prevailing Winds of the U. S., *Annals Assoc. Am., Geographers,* Vol. 6, 1916, pp. 99-116 (abstracted in *Mo. Weather Rev.,* Vol. 47, pp. 575-576, 1919).

[95] See Shaw and others, Meteorol. Glossary, loc. cit., pp. 134-137, 171-173 and also Humphreys: Wind Velocity and Elevation, *Mo. Weather Rev.,* Vol. 44, pp. 14-17, 1916.

change between the wind at the earth surface and that at a moderate elevation. During the day, convection causes masses of air from above to descend to the surface. These layers tend to retain their somewhat different direction of general movement, mentioned in the preceding law. Hence at low altitudes there is a tendency to shift to the right in the northern hemisphere ("veer"). At night, when convection is much less intense or is lacking, the surface friction forces the wind to blow at a larger angle with the isobars and as this adjustment takes place the wind shifts counter-clockwise ("backs"). At higher altitudes, a few hundred feet above the surface in winter and 2,000 or 3,000 feet (610 or 914 meters) in summer,[96] the wind direction changes in the opposite way to that at low altitudes because at night less friction is induced by upward convection than by day, since there is comparatively little convection at night. Hence the air at higher levels can flow at a smaller angle with the isobars by night than it can by day. Along coasts there is often a marked progressive shifting in the land and sea breeze. Sometimes it reaches nearly 90°.[97] This shifting is produced chiefly by the deflective effects of the earth's rotation on the air which comes from a progressively greater distance from the shore line until the breezes finally die down.

WIND VELOCITY.—*Variations with Latitude and Altitude.*

36. *Average wind velocities increase with latitude to about 45° or 55° N. and S., except for the horse-latitude calm belt.*—This is because winds strengthen, on the average, with the steepening of the barometric gradient and the greatest average interzonal gradients are about 45°-55° N. and S. The correspondence between gradient and velocity is not constant, however, because of various influences, some of which are mentioned below. Normally in mid-latitudes, a ten-mile-an-hour (4.5 meter per sec.) surface wind is to be expected when isobars representing a barometric difference in pressure of one-tenth inch (3.4 mb.) are 170 miles (270 km.) apart, a 25-mile (11.2 meter per sec.) wind when such isobars are 70 miles (110 km.) apart, and a fifty-mile wind (22 m. p. s.) when 35 miles (56 km.) apart.[98] Above the surface 1500 feet (460 meters) or so the wind is little affected by surface conditions and hence the relation between gradient and velocity is much closer,

[96] Hellmann, *Mo. Weather Rev.*, Vol. 45, p. 454, 1917; Dunoyer and Reboul, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918. Taylor, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918.

[97] As at the Chicago Crib in July where the wind is normally from the east at 1 P. M. and shifts to nearly due south by 10 P. M., Davis, loc. cit., p. 135. See also Cox and Armington, The Weather and Climate of Chicago, p. 305, 1914.

[98] Walz, after G. Guilbert, in Weather Forecasting in the U. S., p. 140, 1916.

as is also the case at sea. Under such conditions the winds become almost gradient winds. The velocity of gradient winds is almost exactly doubled as the distance between isobars is halved. Where isobars of .3 inch (10 mb.) are about 900 miles (1450 km.) apart, the wind blows about 11 miles per hour (5 meters per sec.), and where about 100 miles (161 km.) apart, the velocity is about 100 miles per hour (45 m. per sec.). The gradient velocity increases, however, with latitude, about 20 per cent between latitudes 40 and 52, and decreases with increasing temperature, about 10 per cent between 32° F. and 104° F. (0° C. and 40° C.).[99] The increase in average velocity with latitude (to about 45 or 55 N. and S.) is also associated with the average increase in storminess to about those latitudes. Furthermore, wind velocities are on the average slight near the equator partly because the deflective effect of the earth's rotation is so small there that the air flows rapidly into an area of low pressure and fills it promptly and then dies away instead of circling round and round as it does in higher latitudes. The decrease in average velocity in polar regions is not due to the total lack of strong winds, for gales, usually of the drainage or the monsoon type but sometimes foehns, often occur locally in polar regions, especially near the edges of glaciers. However, calms are frequent, so the average wind velocity for polar regions is low.[100]

37. *Wind velocity normally increases with altitude, rapidly over an area of much surface friction and less rapidly over an area of little friction,* such as the sea. There is commonly a rapid increase in velocity from the surface up to the height of the taller local objects interfering with air movement (trees, hills, etc.).[101] Above that level the increase is at a much lower rate; between 2000 feet and 3300 feet (600 and 1000 meters) there may be no considerable increase. Above an elevation of a mile or so (2 km.), there is an average increase of between one and two miles per hour (.5-.9 m. per sec.) for each rise of 1000 feet (300 m.), up to an elevation of three to five miles (5-8 km.), an increase in velocity sufficient to compensate for the decrease in density, so that each 1000-foot layer carries the same mass of air past a given

99 Computed from Shaw, Meteorol. Glossary, pp. 172-173.

100 Ward, Climate, p. 174, Wilkes Land in the Antarctic is an exception (Ibid, p. 176). There cyclonic storms are severe. Also see Simpson, G. E., The Meteorology of the Antarctic, *Mo. Weather Rev.*, Vol. 49, pp. 305-306, 1921.

101 The greater velocity commonly recorded at U. S. Weather Bureau Stations in large cities than in small places is because the city aneometers are located on relatively tall buildings. Near the ground the average velocity of the wind is proportional to the 4th or 5th roots of the heights, according to Hellmann, *Mo. Weather Rev.*, Vol. 47, p. 574, 1919. In other words, according to Chapman, (Ibid, p. 572) it is a lineal function of the logarithm of the height.

line per hour. (Clayton's Law, often known as Egnell's Law). The velocity increases to an altitude of about five miles (8 km.), where it often reaches more than 100 miles per hour (45 m. per sec.).[102] Beyond the five-mile level (8 km.), Clayton's Law does not hold, and the velocity falls.

38. *Surface winds average stronger over smooth surfaces than over rough, in similar latitudes* because surface friction reduces the velocity which can occur with a given barometric gradient. Hence winds are normally stronger on water than on land, stronger on plains than over rugged areas, and stronger over grass-covered or barren areas than over forests. A mantle of snow or ice also tends to increase wind velocity by lessening friction. The average velocity of surface winds on the sea is estimated to be twice that of winds on land.[103] Hence along the coasts the average velocity is notably higher than it is a short distance inland. For example, the wind velocity is often only half as great on the east coast as on the west coast of the British Isles, with a west wind and equal barometric gradients.[104]

Effects of Insolation and Humidity.

39. *Winds are often especially strong at the surface by day in places of great insolation.*—This is because convection is strong and hence rapidly moving air from above replaces the warmed air as it rises, in fact causes it to rise. Where much air is quickly warmed, large amounts of rapidly moving air usually descend. Even if they do not descend to the surface, they increase the friction between the surface layers and the faster moving upper layers, which tend to drag the lower air along.[105] The extent of this knitting by day has been discovered by aviators who find that currents induced by local convection are often noticeable at heights of 2000 feet (600 m.) and sometimes 10,000 feet (3,050 m.) or more above the surface on clear days.[106] Hence where a heavy mantle

102 Humphreys, W. J., Wind Velocity and Elevation, *Mo. Weather Rev.*, Vol. 44, pp. 14-17. However, Maurain, C., Ibid, Vol. 47, p. 809, 1919 gives much lower velocities. He reports the maximum velocity experienced by many balloons to be 15.6 meters per sec., (35 miles per hour) and at 11,000 meters 67 miles. Above that height a decrease occurs to about 18 miles per hour (8m. per sec.) at 19,000 m. (12 miles). Velocities in excess of 100 miles an hour (45 m. per sec.) are rare, according to these French balloon data, but one balloon travelled at the rate of 123 miles an hour (55 m. per sec.). A balloon over England travelled 180 miles per hour (80 m. per sec.) at 26,000 feet (7925 m.) on Jan. 19, 1920 Ibid, Vol. 48, p. 41, 1920.

103 Meteorol. Glossary, loc. cit., p. 122.

104 Ibid., p. 123.

105 Pernter, loc. cit., p. 662.

106 Brooks, C. F., Effects of Winds and Other Weather Conditions on the Flight of Airplanes, *Mo. Weather Rev.*, Vol. 47, pp. 523-525, 1919.

of clouds retards insolation, as is often the case in humid climates, the surface wind velocity on a hot day is often much less than on a clear day with its usually greater convection. Often narrow, deep valleys may be nearly calm in spite of intense insolation because the wind, if at right angles to the valleys, may not descend to the floor of the valley before it commences to ascend the other side. An example is Death Valley, California.

40. *Winds associated with rapid convection are strongest in the season and at the time of day when convection is greatest,* which usually is shortly after the time of greatest insolation. Although insolation is greatest and the vertical temperature gradient is steeper just before noon than at noon, convection commonly intensifies for some time after noon, and after the summer solstice. Insolation averages greater just before noon than at noon because of less average cloudiness then; convection is greater shortly after noon and after the summer solstice than when the sun is most nearly vertical because of the lag in surface temperatures (Law 14). Thunder-storms with their associated squall winds occur on the land chiefly in early summer in mid-latitudes and at corresponding seasons in low latitudes. Dust whirl-winds also are most frequent then and near noon. Tornadoes are most numerous in May and June in the northern hemisphere. On the other hand, upon the ocean, in high latitudes especially, the vertical temperature gradient is greatest in winter, because then the surface air is kept relatively warm by the water. Hence high-latitude ocean thunder-storms are most frequent in winter.[107]

41. *With a given barometric gradient, wind velocity tends to increase slightly with absolute humidity,* because water vapor is less viscous and lighter than dry air. (Molecular weight of air is about 29, while that of water is only 18.) The wider average spacing of isobars in the warmer latitudes and in summer is in part an indirect result of this greater amount of water vapor.[108]

Effects of Direction.

42. *Non-planetary winds blowing with the planetary circulation are stronger than similar winds blowing in other directions* because the planetary circulation augments their velocity if they are blowing with it, or checks their velocity if they are blowing against it. This law largely accounts for the "dangerous side" (poleward, right) of tropical cyclones; for the greater velocities on the equator-ward (right) side of extra-tropical cyclones and on the poleward side of anti-cyclones; for the greater influence of sea and lake breezes on the eastern shores

[107] Humphreys, Physics of the Air, p. 324.

[108] Davis, loc. cit., p. 153.

of water bodies in the belt of Westerlies and on the western shores in the Trades; and also for stronger monsoons on one side of some land areas than on other sides quite similar in other respects.

43. *Exceptionally cold winds are often more powerful than relatively warm winds* because such cold winds commonly have a greater velocity and density. The greater velocity is partly caused by the recent descent from somewhat higher altitudes, of which their greater than average downward component is evidence.[109] It is also associated with the steep pressure gradient caused by the exceptionally cold and therefore dense air of the northwesterly winds in contrast to the warm southerly winds usually occurring immediately to the east (in the Northern Hemisphere). Their greater density is related to their low temperature. Their density enables them to push harder than less dense winds. In the northern hemisphere, northwest winds average the coldest. They also average the strongest, for the above mentioned reasons and because they are aided more by the prevailing westerlies than are the winds from most directions.

Seasonal and Diurnal Variation.

44. *Wind velocities average greater in winter than in summer in mid-latitudes.*—The lessened average barometric gradient of summer which largely produces the lesser summer velocity is related to: (1) lessened storminess in summer (most widespread high winds in mid-latitudes are associated with intense Lows); (2) the greater absolute humidity of summer permits a freer wind movement and thus tends to facilitate an equalization of barometric differences; (3) the fact that the isotherms are farther apart in summer than in winter results in the isobars usually being far apart also; (4) the barometric gradients are also affected by the temperature gradients, which often are steeper in winter than during most of the summer. Another factor tending to reduce the velocity of the wind in summer is the greater friction resulting from vegetation and from local contrasts in surface heating with their resulting convectional disturbances. Gales are commonly much more frequent in winter than in summer. For example, on the British coasts, gales are more than six times as likely to occur on any day in the six months October to March, as on a day in the three months June to August.[110]

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109 See H. H. Kimball, Northwest and Southwest Winds Compared, *Mo. Weather Rev.*, Vol. 48, p. 147, 1920.

110 Meteorol. Glossary, p. 127. In some other areas, gales are most numerous in spring. For example, in South Dakota, though there are fewer gales in Dec. and Jan. than in summer, there are more than twice as many in April and May as in July and August. (Visher, S. S., Climate of S. Dak. p. 51, *Bull.* 8, *S. Dak. Geol. Surv.* 1918). In hurricane regions, on the other hand, gales usually are most

45. *The surface winds on the land commonly increase in velocity during the day until early in the afternoon, except at high altitudes on mountain peaks.* The increase in velocity accompanies the increase in convection.[111] It is due to an interchange of surface air and the faster moving higher air. The diurnal increase is greatest when the sky is clear. On cloudy days the maximum surface wind velocity is, on the average, only about half what it is when the sky is clear,[112] because on cloudy days convection is less than on clear days. At many places the average wind velocity is twice as great in the mid-afternoon as it is in the early morning. The diurnal variation in wind velocity almost disappears over the ocean with its nearly constant temperatures, and is less on the land in winter than in summer, and less on cloudy than on clear days, and less in the cooler regions than in warmer, because of the greater convection in summer and on clear days and in low latitudes. At high altitudes some distance above the surface, on the other hand, winds are stronger by night than by day chiefly because fewer convection currents reach a high level at night and hence there is less interference at night with the regular winds.[113] As an example: The average velocity on Pike's Peak is greatest from 2-4 A. M. (23.2 mi. per hour; 10 m. per sec.), and is least just before noon (17.5 mi. per hour; 8 m. per sec.). For the lowlands of the eastern United States, the hour of maximum wind velocity averages 2 P. M. and of minimum velocity 4 A. M., and the difference between minimum and maximum velocity averages two miles per hour (.9 m. per sec.) in winter and five miles per hour (2.2 m. per sec.) in summer.[114] At Kew, England, the diurnal variation averages six miles per hour (2.7 m. per sec.) in July and 2½ miles per hour (1.1 m. per sec.) in winter.[115]

frequent in autumn. (Visher, S. S., Tropical Cyclones of Australia, and the South Pacific and Indian Oceans and in the North Pacific, *Mo. Weather Rev.*, Vol. 50, pp. 288-297, 583-589, 1922).

111 Pernter, loc. cit., Taylor: Phenomena Connected with Turbulence in the Lower Atmosphere, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918.

112 Russell, T., Meteorology, p, 106, 1895.

113 Hellmann, (*Mo. Weather Rev.*, Vol. 43, p. 58, 1915) ascribes this increase to the influence of the thermal wave caused by the earth's rotation. See Humphreys in Nat. Research Council, Introductory Meteorology, pp. 106-107, for additional, though probably very minor influences.

114 Waldo, F., Hourly Wind Velocities, *Am. Meteorol. Journ.*, Vol. 12, pp. 75-89, 145-151, 1895.

115 Shaw, Meteorol. Glossary, p. 86. The great diurnal increase in wind velocity at Hongkong is clearly shown on Plate 13 of Claxton, T. F., The Climate of Hongkong Royal Obs., 1916. The maximum normally is between 1 and 2 P. M. when the velocity averages one-third (4 miles per hour) more than at the minimum which occurs at 8 P. M. during 5 months, at 6 A. M. during 4 months and at 11, 2 and 7 A. M. on the others.

STEADINESS OF WINDS.—*Variations in Latitude and Altitude.*

46. *In general there is a lessening of the persistence of winds with increased latitude accompanying the intensification of temperature variability,** because winds vary in persistence with changes in the permanence of the conditions or conditional complexes that produce them. The Trades are notably persistent because of the steady heating along the thermal equator. Monsoons are less reliable than the Trades because of the greater variation in the heating of continental areas near the borders of the tropics than along the thermal equator. Lake and sea breezes are strongest and most persistent when there is greatest temperature contrast between land and water, as on clear days in hot seasons. Sea breezes are exceptionally prominent on west coasts in the Trade Wind belt for there not only is the land heated greatly by day but the surface ocean water is exceptionally cool by day as compared with the land, largely because of the upwelling of cold abysmal waters induced by the drift to the westward (contributory causes of the coolness are mentioned in Law 5). In general the sea breeze is better developed than the land breeze because the land is warmer than the sea throughout the year in low latitudes and in summer, the season of sea breezes, in higher latitudes.[116]

47. *Winds tend to increase in steadiness with altitude in the free air and on windward slopes, up to considerable heights,* because friction is less and disturbances are fewer.† The change with altitude is especially marked at night. In large parts of the world fitful breezes are the rule at night at the surface on lowlands, while at moderate elevations the wind is blowing steadily. (See next law.) The same condition often obtains on lowlands along coasts, before the sea breeze and land breeze make themselves felt at the surface.[117]

Variation with Diurnal Range of Temperature.

48. *Calm nights are common wherever the surface becomes much colder at night than it is by day,* and hence are characteristic of trade wind deserts and other dry parts of the land. Calm nights are abnormal on the ocean, except in the belts of calms, because of its nearly uniform surface temperatures.[118] Winds commonly die down at the surface of

* See Law 25, above.

116 Hann, loc. cit., p. 160.

† See Laws 37, 38, 45, 48, 49, 50, for some effects of increased altitude on winds

117 Davis, W. M., Elementary Meteorology, p. 136, 1894.

118 Humphreys points out (Physics of the Air) (p. 324) that because of the greater nocturnal cooling of the air than of the surface water, the temperature gradient over the ocean is most favorable to convection shortly before sunrise. Hence convection currents and thunderstorms are most numerous then. Surface wind velocity must also be greatest then, wherever the influence here discussed is dominant.

the land at nightfall because this surface is a comparatively good radiator and since it has a lower specific heat than air, it is soon cooler than the over-lying air. After the surface air is cooled by conduction and moderate radiation to the cooler earth, upward convection largely ceases because the colder, heavier air is at the bottom of the atmosphere. Friction tends greatly to retard the movement of this lower, heavier air. The wind tends to slip over the surface layers, and if it does slip over them a surface calm is induced. The completeness of the surface nocturnal calm depends on the amount of nocturnal convection, the amount of friction, and the character of the wind. In dry regions, loss of heat by radiation is exceptionally rapid, and hence convection largely ceases soon after sunset. There is more friction over land than over water, and more in forested and rugged parts of the land than in grass covered or level areas. Winds with a notable downward component tend to prevent the development of a surface calm, whereas winds with an upward component favor its development. The Trades are of the latter sort,[119] as are the winds blowing into a Low from the equatorward side.[120] Those from a High, and on the poleward side of a Low have a distinct downward component. However, calms are frequent near the center of anticyclones,[121] where there is little or no barometric gradient to induce winds. In respect to latitude, the amount of nocturnal surface calm decreases, among places otherwise similar, with increase in latitude up to the poleward side of the great storm belts, roughly to latitude 55° N. and 45° S. This is because to the poleward of this belt, diurnal range is less, and cloudiness and equatorward blowing winds more frequent.

Sudden Changes (*Gustiness and Puffiness*).

49. *All winds vary in velocity and direction from minute to minute.* —Variation in direction, here called " gustiness " is considered in the following law. Variation in velocity, here called " puffiness," is caused largely by the convectional and frictional forces which produce variations in direction. One additional cause for continual change in velocity is the variation in pressure due to the passage of waves through the air, for example those oscillations associated with the constant shift, produced by the earth's rotation, in the longitude of greatest insolation. Frequent slight variations in air pressure are produced over the sea

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119 Abbe, C.: The Mechanics of the Earth's Atmosphere, a Collection of Translations, *Smithsonian Miscellaneous Collections*, 843, 1893. (Paper by Prof. Oberbeck, p. 186.)

120 Blair, W. R., Planetary System of Convection, *Mo. Weather Rev.*, Vol. 44, p. 192, 1916.

121 Shaw, Meteorol. Glossary, p. 31.

by the water waves and troughs. Tidal waves have some effect on air pressure even over the land. The fall of rain, the roll of thunder, and similar disturbances likewise produce slight variations in pressure. The elasticity of the air and its inertia are fundamentally important in connection with "puffiness." Variations in "puffiness," although always present, increase in amplitude, as expressed in miles per hour, with velocity of the surface wind. Often there is a variation of 10 or 20 miles an hour (4½ to 9 meters per sec.), in a few minutes during a high wind. If expressed in per cents, the momentary increases are greatest when a breeze prevails, for then the velocity may double or triple within a few minutes. "Puffiness" is especially conspicuous over a storm-tossed sea, and it also appears to increase with latitude up to the storm belt. The winds about a well-marked Low are particularly "puffy."

50. *Momentary change of direction or gustiness increases on the average with increased surface friction, with approach to the desert, the equator and the bottom of the atmosphere, and in general with increase in convection and in local contrasts in heating.*—The decrease in gustiness with latitude is due to the fact that convection decreases on the average with increase in latitude. The increase with aridity accompanies a general intensification of convection. Objects which produce friction cause some air to rise and later to fall, in order to pass over the object or over the air which has been piled up as a result of friction.[122] Gustiness decreases with height above the surface because most vertical currents induced by local convection or friction only affect the lower few hundred feet of air, and relatively few affect as much as the lower 2500 feet (760 m.).[123] (Vertical local convectional currents are felt twice as high in summer as in winter in some regions).[124] Local contrast in heating is produced by contrasting types of soil or vegetation, the presence of bare areas, of streams, of small lakes or marshes, and of significant differences in slope or relief. Such differences often produce gustiness because air often rises above the warmer areas and descends over the cooler. Cumulus clouds are striking evidences of

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122 Convection is also caused by overriding of one layer of air by another. Easterly winds especially are lighter than westerly winds and are often overridden. This would tend to produce convection. (Shaw, W. N., *Mo. Weather Rev.*, Vol. 42, p. 198, 1914; and see also Brooks, Kimball and Humphreys, Ibid., Vol. 48, pp. 100, 101, 147; 1920.

123 "Gustiness falls off rapidly in the first 500 feet of ascent, and thereafter it is irregular." Dines, W. H., Meteorol. Glossary, p. 142.

124 Brooks, C. F., Winds and the Flight of Airplanes, *Mo. Weather Rev.*, Vol. 47, pp. 523-525, 1919.

such unequal heating.[125] Wherever and whenever local convection is least, gustiness due to local convection is least. Therefore this type of "bumpiness" is less in the relatively calm, cloudless weather of an on-coming High than in an on-coming Low with its patches of clouds, and its stronger winds.[126] Because of the importance of local convection in producing gustiness, the latter is far less noticeable over the sea than over land,[127] at night than by day, in winter than in summer, and less intense over a fog or low cloud than at corresponding altitudes where such barriers to insolation and convection are not present. The lessened gustiness over the sea and on the land in winter is due to the comparatively slight friction. Gustiness increases with aridity only where surface conditions are similar, which seldom is the condition. In arid regions there usually are few trees, fields, roads and buildings. Hence there is less contrast and less friction. Thus, instead of increasing with aridity, gustiness often decreases. Gustiness was not considered as an aspect of climate until surveyors, astronomers and aviators revealed considerable geographic permanence of differences in "visibility" and in "bumpiness." Surveyors find that the visibility of distant objects usually decreases from morning to mid-afternoon and then increases; that the "seeing" is better on a cloudy day than on a clear or partly clear day; and that on clear days "seeing" is better in cool climates than in warm. These variations in visibility are apparently related to local convection, the great cause of gustiness. Astronomers find the "seeing" poorest on windy nights and best on calm nights. The fact that nocturnal "seeing" is especially favorable in deserts is probably related not so much to less humidity, as to the lack of nocturnal convection. The excellent vision at night at Mandeville, Jamaica, where the annual rainfall normally is 87 inches (2210 mm.), but where, for special reasons, the nocturnal convection is slight, supports this view.[128]

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[125] Another excellent indicator of convection and of turbulence due to friction is smoke from a smokestack. See Etkes and Brooks, *Mo. Weather Rev.*, Vol. 46, pp. 459-460, 1918.

[126] Shaw, Meteorol. Glossary, pp. 21-23.

[127] Taylor, loc. cit.

[128] Pickering, W. H., *Mo. Weather Rev.*, Vol. 47, p. 574, 1919; and Vol. 48, p. 511, 1920.

LAWS CONCERNING ATMOSPHERIC MOISTURE

Sources of Moisture.

51. *Atmospheric moisture is derived by evaporation from all moist surfaces, chief of which is the ocean,* as the ocean covers three-fourths of the globe and more than four-fifths of its warmer half. Evaporation from soil, vegetation, animals and water on the land is the immediate source of much vapor. It should be borne in mind however, that a lake, even a large lake, is no more an ultimate source of water vapor than is ground moistened by a shower; both are temporary resting places of water en route to the sea. Nevertheless, much rainfall on the land is derived from moisture recently evaporated from such resting places. The small amount of evaporation taking place at low temperatures during the winter, when there is often much snow or other moisture on the ground, is one cause for the lesser precipitation in the cold season than in the warm in many inland places. When spring comes with its higher temperatures, accumulated moisture of the winter is soon largely evaporated and often partly reprecipitated, giving rise to spring showers. Some of it remains in the air, however, until the autumnal cooling.

Rate of Evaporation.

52. *The potential rate of evaporation at any point normally increases with the temperature and hence usually is greatest at the warmest time of the day and year.* At night condensation often takes place instead of evaporation. This variation occurs because the capacity of space to hold moisture increases sharply with the temperature. Twenty times as much moisture can be contained in a given space at 100° F. (38° C.) as at 15° F. (—9° C.).[129] The capacity is approximately doubled or halved with each change of 18° F. (10° C.). The local rate of evaporation is affected also by the wind velocity and, as there commonly is also a diurnal intensification of wind velocity corresponding with the diurnal rise of temperature,[130] the wind regime helps explain the diurnal change in evaporation. The wind is significant as a factor affecting the rate of evaporation because it carries away the saturated or partly saturated air. When other conditions

129 Tables of capacity in vapor pressure and in quantity of water vapor per cu. ft. at different temperatures are given by Milham, Meteorology, p. 195, and in texts on physics. A full table showing vapor pressure for relative humidities at different temperatures is given in *Smithsonian Meteorol. Tables,* pp. 183-185 and pp. 192-193, 1918.

130 The close similarity of the diurnal curves of temperature and wind velocity is strikingly illustrated at Chicago. See Cox and Armington, Weather and Climate of Chicago, p. 314, 1914.

are uniform, the rate of evaporation is roughly proportional to the square root of the wind velocity.[131] The influence of the higher average velocity of wind in winter, however, is usually counteracted by the lower temperatures.

The rate of evaporation depends also upon the humidity of the air in contact with a moist surface and the temperature of that surface. If the surrounding air contains much less moisture than it can hold at its temperature, evaporation will be relatively rapid; if it is nearly saturated, evaporation will be relatively slow. If the moist surface is warm, evaporation is more rapid than if it is cold. The more rapid evaporation on clear days than on cloudy days in mid-latitudes is due chiefly to the fact that air is commonly drier on clear days than on cloudy days, even though it is sometimes cooler. The greater insolation in clear weather is significant because it tends to maintain the surface temperature, and thus allows evaporation to continue at a faster rate than the dry air alone would permit. Clear days in mid-latitudes usually are associated with anticyclones in which the air is descending and being warmed dynamically.

53. *The rate of evaporation diminishes on the average at progressively higher latitudes and altitudes and also with approach to marine conditions.* The change with latitude is associated with a like change in temperature. The Trades are drying winds except where ascending because they blow into progressively warmer latitudes. Decrease in the rate of evaporation with approach to marine conditions is influenced by increased relative humidity, and in all but cold places, also by lessened average temperatures. Within the tropics there is an average annual evaporaton of 30 inches (760 mm.) and in the polar regions less than 10 inches (250 mm.). In general, evaporation exceeds precipitation in the lower latitudes while precipitation exceeds evaporation in the higher latitudes.

The general decrease in evaporation with increase in altitude is the result of lessened temperatures and this decrease takes place in spite of the influences of decreased air pressure, lower absolute humidity, and stronger winds, all of which tend to increase the rate of evaporation. Hence, whenever temperatures at high altitudes are equal to those at low altitudes the rate of evaporation tends to increase with altitude. Furthermore the low absolute humidity characteristic of high altitudes strikingly affects the rate of evaporation whenever temperatures are suddenly raised. When cold air, saturated perhaps but containing only a little moisture, is warmed, it becomes relatively dry, and thus evaporation is facilitated. Marked surface heating by insolation, which

[131] Hann, Handbook of Climatology, Vol. 1, translated by Ward, p. 44, 1903.

is fairly frequent at high altitudes and occasional in high latitudes, thus often results in abnormally low relative humidities and also in rapid evaporation. The influence of decreased pressure upon evaporation where temperatures are high is illustrated by changes in the boiling temperature of water (a form of rapid evaporation). There is a lowering of 1° F. for each decrease in pressure of about .6 in. (1° C. for 37 mb.). Each rise of 550 ft. (178 m.) produces such a change in average pressure. Water boils, at all levels, at a lower temperature, sometimes as much as 3° F. (1.7° C.) lower, in a Low than in a High.[132]

DISTRIBUTION OF MOISTURE.

54. *The windward sides of continents and of mountain ranges receive much more moisture, and hence more precipitation, than do the leeward sides* because atmospheric moisture is transferred chiefly by the wind. Diffusion is so slow a process that calms of sufficient duration to make diffusion significant are rare. Streams are the only other agent distributing much moisture. Rivers such as the Volga and Nile which carry large volumes of water into arid regions where it evaporates doubtless have some influence on the amount of atmospheric moisture in parts of their basins. The influence of winds on this distribution of moisture is illustrated in many places. For example, in the Hawaiian Islands an average of over 476 inches (12.1 m.) of rain falls annually on Mt. Waialeale, alt. 5075 ft. (1550 m.) on Kauai, while only 16 inches (406 mm.) falls on the leeward slope only 11 miles (18 km.) away. On another island (Maui) two stations only 7½ miles (12 km.) apart receive an average of 369 inches and 18 inches (9373 mm. and 457 mm.) respectively.[133] In the belt of Westerlies the condition near Seattle, Washington is noteworthy. Fifty miles west of Seattle, on the windward slope of the Olympic Mountains, the average precipitation is more than 120 inches (3500 mm.). At Seattle it is only 42 inches (1070 mm.) and an average as low as 18 inches (457 mm.) of rainfall occurs on some of the nearby islands in Puget Sound. Thirty miles east of Seattle, on the western slopes of the Cascades, more than 80 inches (2030 mm.) falls. A hundred miles east of Seattle, just east of the Cascades, the average precipitation is less than 10 inches (250 mm.).[134]

55. *The amount of atmospheric moisture (absolute humidity) nor-*

[132] Shaw, Meteorological Glossary, p. 300.

[133] Summary of Climatological Data for the Hawaiian Section, 1922 and *Mo. Weather Rev.*, Vol. 47, pp. 303-305, 1919.

[134] Chart of Average Annual Precipitation in the U. S., Atlas of American Agriculture, 1917. Reprinted in *Mo. Weather Rev.*, Vol. 45, Plate 76, 1917.

mally varies inversely with latitude and altitude, and as a rule, directly with distance from the sea,[135] because absolute humidity increases with the hastened evaporation which is induced by higher temperatures, and because warm air (space) can contain more moisture than cold. Water vapor makes up an average of 2.63% of the surface air at the equator; .92% at latitude 50 N. and .22% at latitude 70 N. The average for the earth is 1.2%.[136] Sometimes water vapor makes up as much as 5% of the weight of the air present over water bodies in warm areas.[137] This is equivalent to a vapor pressure of more than 1½ inches (38 mm.) of mercury. The atmosphere of the warmer half of the globe contains fully four-fifths of the total atmospheric moisture. The average decrease with latitude is illustrated in North Dakota, Nebraska, and Oklahoma, all of which are inland states in the same longitude and with similar amounts of rainfall. The average of the 7 A. M. and 7 P. M. vapor pressures for January, April, July and October is .20 in. (5 mm.) for North Dakota; .25 in. (6.3 mm.) for Nebraska; and .35 in. (9 mm.) for Oklahoma.[138] Decrease in absolute humidity with latitude is also illustrated by the statement that the air over Europe contains on the average enough moisture to yield about an inch (25 mm.) of water if it were all condensed, while condensation of all the atmospheric moisture over the eastern half of the United States would yield nearly 2 inches (50 mm.).[139]

The poleward decrease in vapor pressure is however not at a uniform rate. It varies with the effective distance from water bodies, with average temperatures, and with altitude.[140] In the storm belts, it is probably less than the expected normal for that latitude because the increased upward convection and precipitation in storms tend to lessen the absolute humidity.

Vapor pressure usually decreases inland rather rapidly. It often is approximately twice as great along the coast as in the drier portions of the continental interior in the same latitudes. This decrease is due to the fact that the moisture evaporated from the ocean and precipitated inland is not replaced by a like amount evaporated from the land.

The average decrease in water vapor with increase in altitude is

135 Day, P. C., Relative Humidities and Vapor Pressures over the United States, *Mo. Weather Rev., Supplement*, No. 6, pp. 5-61 and 24 charts, 1917.

136 Hann, Lehrbuch der Meteorologie, 3rd ed., p. 5, 1915.

137 Day, loc. cit., p. 6.

138 Calculated from data given by Day, *loc. cit.*

139 Day, *loc. cit.*

140 See also Table of Monthly Mean Water Vapor Pressures for Eastern, Central and Central Plateau States for four different latitudes given in *Mo. Weather Rev.*, Vol. 47, p. 772, 1919.

sharp. One-half the atmospheric moisture is within a mile (1.6 km.) of sealevel and at six miles (10 km.) the air contains only 1/120 as much as at sealevel.[141] This diminution is chiefly due to the decrease in temperature and hence in capacity, but in part to the fact that the atmosphere is supplied with moisture from below. Indeed all primary evaporation takes place at the bottom of the air.

56. *The absolute humidity is greater by day than at night, greater in summer than in winter and greater during wet periods than during dry periods.* The increase by day and in summer is related to the higher temperatures prevailing. The increased vapor pressure which commonly accompanies wet periods is caused chiefly by the larger supply of moisture from the sea brought inland by the winds. However, the larger amount of surface water and ground water available for evaporation, and actually evaporated, also plays a part.

The average diurnal increase of absolute humidity for the United States amounts to about 15%.[142] The increase is greater in summer than in winter especially if the actual increase and not the percentage of increase is considered. This is because a diurnal range of 30° F. (17° C.), for example, produces a greater change in the amount of moisture held if between 50° F. and 80° F. (10° C. and 27° C.) than if between 0° F. and 30° F. (—18° C. and —1° C.). Furthermore, nocturnal precipitation and dew and frost often greatly reduce the atmospheric moisture at night. In England, a country with high average humidity, the mean diurnal range is about 6%, varying from 5% in December and January to 8% in June and September. Among the months, there is nearly twice as much moisture in the air in July and August as in January and February.[143]

On the average, the vapor pressure is least about sunrise and greatest near mid-day. On the land the maximum comes shortly before noon in all warm places. On the other hand, it comes in the early afternoon in cool places such as the sea, and the land in winter. The normal relationship between absolute humidity and temperature, however, is often interfered with by convection. Hence wherever convection is intense, the absolute humidity at the surface of the earth usually is less shortly after mid-day than at any other time, because the warm moist air is then more easily displaced by drier air brought down by convection. In dry regions when convection is strong, there is often

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141 Humphreys, Physics of the Air, p. 69, 1920.

142 Computed from Day, *loc. cit.*

143 Meteorol. Glossary, *loc. cit.*, pp. 290-292. The monthly and diurnal variations in humidity are clearly presented for Hongkong, in Claxton, The Climate of Hongkong, 1916.

a decided decrease in vapor pressure as the hour of maximum temperature and convection approaches, because there is not enough evaporation to replace the moisture carried aloft by intense upward convection. Places, which because of nocturnal "inversion of temperature" have calm nights, may occasionally have more moisture in the surface air in the evening than at 2 P. M.

The seasonal range in absolute humidity depends upon the seasonal change in temperature or wind direction. For places having cold and warm seasons, the maximum occurs in the warmest season and the minimum in the coldest, and there is a difference in humidity corresponding to the contrast in temperature. For example, the vapor pressure in North Dakota averages about nine times as much in July as in January; in Nebraska, six times as great; in Oklahoma four times; in Louisiana 2¼ times; at Key West, Fla., where there is little seasonal contrast in temperature, the vapor pressure of the highest month (August) is .83 in. (21 mm.) whereas in January it is two-thirds as great (.56 in., 14 mm.). These figures indicate also that the annual range in vapor pressure increases with latitude, which is in keeping with the increase in temperature range.[144]

RELATIVE HUMIDITY.

57. *Relative humidity increases, on the average, with latitude and altitude and is greater along the coasts than inland.* In general it increases as absolute humidity decreases. The increase in relative humidity with latitude and altitude accompanies a normal decrease in temperature and hence in capacity for holding moisture. The increase with latitude on the land is illustrated along practically every meridian on Day's maps of relative humidity for the United States[145] in spite of the conspicuous influence of the western highlands on the distribution of moisture. The following annual averages from 7 A. M. and 7 P. M. for places having almost the same precipitation (between 20 and 25 inches) (508-635 mm.) illustrates the influence of latitude: Fargo, N. D., 79%; Huron, S. D., 72%; North Platte, Neb., 70%; Dodge City, Kan., 66%; Abilene, Tex., 64%. Even where the precipitation decreases notably from south to north, as in the following places, the average relative humidity increases with latitude; Chicago, 74%; Milwaukee, 75%; Escanaba, Mich., 79%; also Louisville, Ky., 69%; Indianapolis, Ind., 72%; Grand Rapids, Mich., 76%; and also St. Louis, Mo., 70%; Madison, Wis., 75%. The increase with latitude is made

144 Computed from Figs. 4 and 5 in Day *loc. cit.*

145 Day, *loc. cit.*

irregular, however, by variations in the distance from the sea.[146] The average relative humidity over the sea is about 85%, while that over the continents is perhaps 60%,[147] ranging from 50% or less in the drier regions to nearly 85% along the coasts. Upon the sea, the normal relative humidity is about 82% in low latitudes and 92% in high latitudes.[148] Relative humidity does not increase normally with latitude between the equator and the centers of the Trade Wind deserts.

The increase in relative humidity with altitude is not rapid and is limited by the cloud zone, above which the air is somewhat drier. The increase is not so great as the temperature gradient would suggest because moisture is supplied only from moist surfaces at the bottom of the atmosphere and there is progressively less and less moist land at higher altitudes. Thus high altitudes often have dry air when saturated air would be expected on the basis of the normal, though often small, increase of relative humidity with altitude. Dryness is much more common on the leeward side of mountains than on the windward side. Such dryness usually is related to a foehn or is produced by an excessive settling of higher layers of air such as often cause the dispersal of clouds at night. (See Law 65.) A third way in which the air at high altitudes is sometimes made intensely dry is given in Law 53 above. This principle operates to make the air dry when in contact with the warm skin. Whenever the cold air of high altitudes and latitudes is warmed by contact with warm skin it becomes distinctly dry and causes rapid evaporation. Thus very cold air affects man like dry air because as it is warmed by contact it becomes relatively dry. This is nearly as true of cold air which was originally saturated as of air which was dry before coming in contact with man.

58. *Relative humidity increases as air ascends and decreases as it descends. Hence relative humidity is greater on windward slopes than on leeward slopes.* This is because the capacity of space for moisture decreases with the temperature. Ascending air is cooled by expansion and by accelerated radiation. Heat lost in these ways is less and less fully replaced at higher altitudes partly because of the increased distance of the air from its chief source of heat,—the surface of the earth,—and because of the interception of heat at lower levels. On the other hand, descending air is warmed by compression and by

146 In winter in cold regions, the relative humidity often increases inland accompanying the decrease in temperature inland (Hann, Handbook of Climatology, Vol. 1, p. 151).

147 Salisbury, Physiography, p. 495, 1919.

148 Waldo, Elementary Meteorology, p. 127, 1896.

coming to lower and warmer altitudes. As it is warmed it becomes relatively drier. Under favorable conditions the air becomes warmed conspicuously and is made very dry, producing a foehn.

59. *Atmospheric humidity, both absolute and relative, averages less at the earth's surface in windy areas than in calm areas otherwise similar,* because in windy areas, the moistened lower layers of air are soon mixed with or replaced by drier air from above. Upward convection is the agent which does most to prevent the surface air from being excessively humid. As water vapor is lighter than the other constituents of the surface air, moist air is forced to rise and is replaced by heavier and drier air. The height to which it can ascend is limited by condensation and by gravity. An exception to this rule of decreased humidity with increased windiness often occurs in the centers of Highs, where, in spite of slight windiness, humidity is often relatively low because of descending air.

60. *Relative humidity of the surface air averages greater by night than by day, greater in winter than in summer, greater in cool periods than in hot periods and is also greater before than after precipitation.* The lower humidity by day in summer and during hot periods is related to the higher temperatures and the greater mixing of the surface with the drier air above at those times. The warmest time of the day, year or period normally has the lowest relative humidity because the capacity of the air (space) is greatest then. The highest relative humidity usually occurs at the coldest time. However, the coldest weather of winter in mid-latitudes is not often accompanied by the highest relative humidity because such weather is often caused by a cold wind from higher latitudes or by air descending from somewhat higher altitudes, and such air is relatively dry.[149] In general, as the temperature goes up the relative humidity goes down, and *vice versa.* However, after the dew point is reached a further increase in relative humidity is impossible; instead it stays at 100% when the temperature falls still lower.

61. *In general, seasonal and diurnal ranges in relative humidity vary in harmony with range in temperature, and therefore are commonly great in arid regions and in continental interiors, and small over the sea and most snow-covered areas.* Annual range increases toward the equator, with nearness to the ocean or lakes, with aridity, with altitude (up to the cloud zone or snow-line), and with decrease in vegetation. It is also affected by cloudiness and windiness. The amplitude is several times greater on clear than on cloudy days and

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[149] This condition is illustrated locally within the tropics, where the winter winds come from the north, as at Hongkong. See Claxton, *loc. cit.*

it is especially small on continuously rainy days. The range is smaller when the wind blows steadily than in times of fitful winds or calm. The increase in relative humidity before precipitation is sufficiently marked in many places to be useful in forecasting the weather.[150] Several of these kinds of variation in relative humidity are illustrated by the following figures, from Day's tables.[151] At Burlington, Vt., the average winter (December, January and February) maximum (about sunrise) and the average winter minimum (about 2 P. M.) are 79% and 67% respectively; in summer (June, July and August) 84% and 53% respectively; at St. Louis, Mo., the corresponding figures are 74% and 54% (winter) and 71% and 50% (summer); at Sheridan, Wyo., 84% and 56% (winter) and 82% and 37% (summer). Waldo gives the diurnal amplitude for the northwestern coast of Europe as 7% in December and 17% in August; for Nukuss in central Asia, 26% in December and 50% in summer.[152]

Abnormally low relative humidities occur occasionally in the surface air. Such departures are much more extreme over the land than over the sea and in dry regions than in wet. In arid regions in the United States humidities as low as 3% occasionally occur and in humid regions as low as 10%.[153] Abnormally low relative humidities are caused by a sharp rise in the temperature of the affected air. In rugged areas, foehns often cause extreme dryness. Perhaps the free-air foehn[154] is not rare in connection with cyclonic storms. The intense downward movement produces the relative dryness.

CONDENSATION.

62. *As condensation occurs whenever air is cooled below the saturation point, it is most frequent at night and in winter, except such as is due to convection which is most frequent when convection is most intense, namely during the day and in summer,* over the land. Nocturnal and winter cooling sufficient to cause condensation is due chiefly to chilling induced by loss of heat by radiation from the surface to the overlying air, or from the air downward to colder land or water. Loss of heat by conduction is important where good conductors are involved. Condensation is sometimes caused by the mixture of cold

150 Garriot, E. B., Weather Folklore and Local Weather Signs, *U. S. Weather Bureau, Bull.* 33, pp. 20-22, 1903.

151 Day, *loc. cit.*, pp. 13-61.

152 Waldo, Elementary Meteorology, p. 125, 1896.

153 Day, *loc. cit.*, p. 10. At Hongkong, where the average rainfall is 83 in. (2110 mm.) relative humidities as low as 5% have been recorded in winter. (Claxton, *loc. cit.*)

154 Brooks, C. F., A hill-top foehn, *Mo. Weather Rev.*, Vol. 47, p. 567, 1919.

air and warm air, as when a cold wind is blowing over warm water. Most clouds are caused by convection. Ascending air is cooled by expansion at the rate of 1.6 degrees F. for each 300 feet of ascent (1° C. per 103 meters), until condensation occurs.[155] Dew, frost and fog usually appear by night and disappear by day, because of the diurnal range in temperature and in relative humidity. (For clouds see Law 65, beyond.) The greater frequency of condensation in winter is illustrated at Chicago, where, in spite of the fact that much more rain falls in summer than in winter, precipitation is 30% more frequent in winter than in summer.[156]

63. *The frequency of condensation tends to increase with latitude, with humidity and with altitude,* up to the cloud level. Except where deserts are involved, cloudiness increases with latitude, though in high latitudes the clouds commonly are thin. Sealevel fogs often persist throughout the day in high latitudes, but not in low latitudes. Frost also frequently does not disappear by day in high latitudes while dew practically always disappears by day in low latitudes. Snow and rain disappear slowly in the higher latitudes. The frequency of dew and frost formation tends to increase in any latitude with increase in diurnal range. Dew seldom forms on shipboard at sea. In arid regions the relative humidity often is so low that condensation does not occur even when the diurnal range is great. The persistence of frost or fog by day in high latitudes is greatest where the diurnal range is small, as over snowfields or on the sea.

64. *The amount of condensation decreases, on the average, with latitude, except in the Trade Wind deserts, and also with altitude above a few thousand feet.* The amount of condensation depends on the absolute humidity of the air, the amount of vapor cooled, and the extent of cooling. In the rainy tropics, where the absolute humidity is great, as much as one-tenth of an inch (2.5 mm.) of dew gathers during some nights.[157] In mid-latitudes a hundredth of an inch is a heavy dew. Clouds generally decrease in thickness and density with increase in latitude and with increase in altitude above three thousand feet (900 m.). In high latitudes the sun or moon can often be seen through clouds. Indeed, in polar regions it often snows from an almost clear sky.

The normal relationship between latitude and condensation is disturbed by the distribution of atmospheric dust. Cities, with their vast

[155] Humphreys, Physics of the Air, p. 31, 1920.

[156] Cox and Armington, The Weather and Climate of Chicago, p. 168, 1914.

[157] Von Bezold, Wm., in Abbe, C., Mechanics of the Earth's Atmosphere, *Smithsonian Misc. Collect.*, p. 283, 1893.

quantities of soot and hygroscopic dust, are sites of undue condensation, and their air nearly always has more haze than is normal for the latitude. In many cities the persistent haze is called smoke, and in others, in cool moist climates, it is often a fog. This is due chiefly to the condensation upon atmospheric dust which is a better radiator than air, and thus often cools below the dewpoint. In moist regions condensation upon the cold dust particles frequently occurs, and thus the dust acts as nuclei of fog particles. If dust particles suitable to serve as nuclei are not present in sufficient abundance, considerable super-saturation may precede condensation. In nature, however, there apparently is always sufficient dust present.[158]

65. *The amount of condensation varies from time to time with variations in the intensity of temperature changes and with the humidity.* Hence dew and frost form most abundantly when the nocturnal cooling is rapid. Because of the lessened absolute humidity following condensation, the rate of dew and frost accumulation normally declines soon after the dew-point is passed. This often occurs early in the evening. There is also a marked diurnal variation in the amount of cloudiness.[159] However, as clouds are usually formed by convectional cooling rather than by cooling by radiation, the amount of condensation represented by clouds tends to vary with convection. Therefore cloudiness usually increases by day whenever convection is marked because convection increases until the warmest time of the day is reached. Upward convection often brings bodies of air to heights where the saturation point is passed. After normal convection has reached its maximum, which commonly occurs between 2 and 3 P. M., cloudiness may increase for a time because of further cooling of air brought almost to the dew point by convection. This continued cooling is facilitated by the lessened insolation which accompanies the decrease in the angle of incidence and the development of higher clouds. The sky often clears at night because of the descent of the clouds instead of becoming overcast as would be expected where the nights are cool. At night, when convection largely ceases, the clouds are pulled downward by gravity. Often when once they are descending relatively rapidly, inertia prevents their stopping until they are sufficiently warmed dynamically to evaporate the condensed moisture. The fact that the higher air is often warmer at night than the surface air, because free air cools slowly, is also of importance in this connection. The amount of condensation to form clouds also tends to vary directly with the intensity of convection according to the season. This is true

158 Shaw, W. N., Law of Saturation, *Mo. Weather Rev.*, Vol. 42, p. 198, 1914.

159 Cox and Armington, *loc. cit.*, p. 260.

in spite of the fact that the percentage of cloudiness commonly is greater in winter, when convection is least, than in mid-summer when it is greatest.[160] Winter clouds, however, are normally at low altitudes and relatively thin, their volume and mass being usually less than that of the scattered clouds of a partly cloudy summer day. In summer, when the sun is high its rays often penetrate an amount of condensed moisture sufficient to form what in winter would appear to be a cloud-cover.

PRECIPITATION: KINDS OF.

66. *Precipitation varies in kind from place to place.* While perhaps four-fifths of the world's precipitation is in the form of rain, yet in high latitudes and altitudes, snowfall is important. Moreover sleet and hail have considerable significance. In respect to rainfall, notable differences in size of drops and in intensity of fall occur. Sleet is relatively of most importance in cyclonic climates in coastal regions in fairly high latitudes. Hail, which is always associated with intense convection, is probably most frequently formed in low latitudes. However, as a result of the rapid melting during descent relatively little hail reaches the ground in tropical lowlands. Hence hail is most frequently experienced in latitudes 20°-40°, although it falls in considerable quantities in lower latitudes. For example, ten hailstorms of a destructive character were reported in a decade in latitudes 13°-16° S. near sealevel in Australia and three hailstorms occurred in Panama (latitude 9°) in a 12-year period.[161] On the other hand, several local hailstorms occur each year in subtropical Australia,[162] and in southeastern United States.

The smallest average sized raindrops probably occur in cool marine climates where the normal precipitation is a drizzle.[163] The size of characteristic drops increases in general toward the equator and with increased aridity accompanying a similar increase in the intensity of convection. As to the rate of fall, the heaviest rains occur in low latitudes, and in general there is a progressive decline poleward in the maximum rainfall received in a day or an hour.[164] This decline is

160 *Ibid.*, p. 267.

161 Visher, S. S., Hail in the Tropics, *Bull. Am. Meteorol. Soc.*, Vol. 3, pp. 117-118, 1922.

162 Commonwealth Bureau of Meteorology, Charts of Hail Storms, Melbourne, 1913-18.

163 In Netherlands, for example, four days of each normal week are classed as rainy and yet only 28 inches (711 mm.) is received in the entire year. (Kan, C. M., in Mills International Geogr., p. 219, 1907.)

164 For the United States, see charts of maximum rainfall in 24 consecutive hours and in one hour, *Mo. Weather Rev.*, Vol. 50, p. 119, 1922.

due chiefly to a similar decrease in intensity of convection as is illustrated by the lesser frequency of thunderstorms.[165]

67. *Most places experience seasonal variations in the kind of precipitation.* Snow often falls during the winter in middle and high latitudes, while rain often falls even in polar regions in summer.[166] Hail is characteristic of the season of most intense convection, which, for all but a few points, is shortly after the period when the sun is most nearly overhead. In respect to rainfall, there normally is a seasonal variation in size of drops, in intensity of downpour and in the velocity of fall. Winter rain commonly is made up of smaller drops than summer rain, and falls more slowly and more steadily. Downpours and "cloudbursts" are to be expected at the time of most intense convection.

PLACE DISTRIBUTION.

68. *Precipitation normally is heavy on the windward slope of steep high or cool mountains in relatively warm regions* because wherever a large volume of warm moist air is cooled notably below the saturation point, much condensation occurs (See Law 54). Rapid cooling of warm air is also often accomplished by rapid convectional ascent, where insolation is intense and therefore thunderstorms yield much rain. Precipitation is much less heavy when cold air is further cooled. Hence in uniformly cold regions, mountains have much less effect than in warm regions. The steepness of the slope is significant because convectional overturning is often induced by rather low elevations possessing a steep slope on the windward side.[167] Minor causes of air cooling are chilling by a cold wind, and contact with a cold surface (without ascent). Drizzles and fogs are often formed in these ways. The heavy precipitation in the doldrum belt and by thunderstorms elsewhere, the rainy character of the windward slopes of mountains in the Trade Wind belts and elsewhere, are all illustrations of this law.[168]

69. *Precipitation decreases irregularly in amount with increase in latitude, and in effective distance from the ocean.* The average precipitation for the globe is about 20 inches (508 mm.). The heaviest rainfall on the land of any entire latitude is in the doldrum belt (80 inches (2000 mm.) or more), and the least normal precipitation is perhaps in the polar regions (less than 10 inches; 250 mm.). While

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[165] *Ibid.*, p. 122, Distribution of Thunderstorms in the United States.

[166] Stefansson, V., The Friendly Arctic, 1921.

[167] The importance of the inclination of the slope is emphasized by Pockels, F., Precipitation on Mountain Slopes (1901) translated in C. Abbe third series of the Mechanic of the Earth's Atmosphere, *Smithsonian Collections*, No. 1869, p. 101, 1910.

[168] See Laws 54 and 71 for concrete illustrations.

the Sahara and many other parts of the Trade Wind belts receive no more precipitation than do the polar regions, the average for the Trade Wind belts is raised notably by the precipitation received on the windward slopes, as is illustrated in Law 54 above. The scanty precipitation in polar regions, as at high altitudes, is due largely to the small amount of moisture in the cold air, but the slight convection there is also a factor. The poleward decrease in precipitation is illustrated on all continents.[169] The decrease with latitude is at a higher rate on the continents than on the ocean, for although in the tropics more rain falls on the land than on the sea, the reverse is true in high latitudes.[170] Not only is there a decrease in total rainfall, but there is a corresponding decrease in intensity. In Australia, for example, the number of days on which 5 inches (127 mm.) or more of rain has fallen, decreases steadily and sharply poleward.[171] The same occurs in the United States[172] and elsewhere, except where east-west mountain ranges, such as the Himalayas, form complicating factors by causing marked condensation. All the records of 30 inches (760 mm.) or more of rainfall within 24 hours are from tropical latitudes, as are nearly all records of falls in excess of 10 inches (254 mm.) in 24 hours.[173] In the United States, for example, in twenty years the only areas receiving over 10 inches (254 mm.) in 24 consecutive hours were along the Gulf Coast. No area in the northern third of the country received over 6 inches (150 mm.) while nearly five-sixths of the northern border had an extreme maximum of less than 4 inches (100 mm.).[174]

70. *Precipitation increases with altitude to moderate heights and then decreases steadily and sharply until at the height of 2 or 3 miles (3-5 km.) it is slight.* The maximum precipitation on mountains takes place at an elevation of about 3300 ft. (1000 m.) in the tropics, and about 4500-5000 ft. (1370-1520 m.) in mid-latitudes.[175] The altitude of the zone of maximum precipitation depends upon the relative humidity and temperature of ascending air. Therefore the height

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169 See Herbertson's rainfall maps in Bartholomew's Physical Atlas, 1899.

170 Moore, John, Meteorology, p. 223, 1910 (quoting Herbertson).

171 See lists of heavy rainfalls, Hunt, H. A., The Climate and Meteorology of Australia, Official Yearbook, pp. 59-63, 1920.

172 See Precipitation Section of Atlas of American Agriculture (partly reproduced in *Mo. Weather Rev.*, Vol. 50, pp. 117-124, 1922.

173 Visher, S. S., Variability vs. Uniformity in the Tropics, *Scientific Monthly*, Vol. 15, pp. 28-31, 1922.

174 Precipitation Section of Atlas of American Agriculture, *loc. cit.*

175 Henry, A. J., Increase of Precipitation with Altitude, *Mo. Weather Rev.*, Vol. 47, pp. 33-41, 1919. A thoroughgoing exposition of the subject.

fluctuates with the seasons, being lowest in winter, when low temperatures cause prompter precipitation, than in summer when the relative humidity at any given level is less than in winter.[176] The rate of increase up to the zone of maximum rainfall varies with the total rainfall, being 100 in. for each 1000 ft. (830 mm. per 100 m.) for example, in portions of the Himalayas, 40 in. per 1000 ft. (333 mm. per 100 m.) in Java, and only 2 in. per 1000 ft. (17 mm. per 100 m.) in arid portions of Africa and South America.[177] However, when expressed in percentages, the rate of increase is somewhat similar even in such diverse cases as these, for the increase with each 1000 or 1500 ft. (300 or 450 m.) of altitude is approximately equal to the total rainfall at the base of the slope. Above the zone of maximum rainfall, the decrease is rapid. At high altitudes, it is chiefly in the form of "finely pulverized snow or a drizzle."[178]

71. *Local contrasts in the amount of rainfall are greater in tropical than in higher latitudes among topographically similar places, with the exception of the doldrums.* Local contrasts in humidity, evaporation and wind likewise commonly decrease with latitude. It is probable that tropical, mountainous, oceanic islands have the greatest local climatic differentiation while polar regions have the least. Near the poles even a high mountain causes relatively little local differentiation. In low latitudes one side of many moderate elevations is distinctly more humid than the opposite side, and there is a sudden change in humidity and precipitation with altitude even on the windward slope. Both wind direction and altitude influence the rainfall of many small areas. For instance, within the city of Honolulu the average rainfall ranges from less than 25 in. (635 mm.) to over 90 in. (2290 mm.) at a place of similar elevation only 5 miles (8 km.) distant. Also within 4 miles (6 km.) of the central station with its 31 in. (790 mm.) of rain there is a station with an elevation of 1360 ft. (414 m.) and an average rainfall of 106 in. (2700 mm.). On another of the Hawaiian Islands, Kauai, apparently the rainiest official rainfall station on the globe and with an average of over 476 in. (12.2 m.), is 11 miles (18 km.) distant from a station which receives less than 20 in. (508 mm.).[179] In middle and high latitudes there normally is relatively little contrast in rainfall between the sides of single ranges since the winds come into cyclonic depressions from all directions in

[176] Hann, J., Lehrbuch der Meteorologie, 3rd ed., 1915.

[177] Henry, *loc. cit.*, p. 34.

[178] Hann, Lehrbuch, quoted by Henry, *loc. cit.*

[179] Climatological Data, Hawaiian Section, 1922, supplemented by annual reports for 1919-21 inclusive.

turn, instead of chiefly from one direction as in the tropics. Hence one side normally is very dry in higher latitudes only in case the winds are prevented by some other range from bringing moisture to it. Consider the relatively slight contrast in rainfall on the different sides of the Appalachians, Alps and Caucasus, in comparison with the great contrasts found on most tropical ranges. The local change in rainfall, which accompanies change in altitude, also is less in higher latitudes than in low because there is less change in capacity for moisture when cool air is further cooled than when warm air is cooled a like amount by being forced to rise.

Other causes of greater local differentiation in climate in low latitudes than in high are (a) the steeper vertical temperature gradient, so that corresponding changes in altitude produce greater changes of temperature in the tropics than in high latitudes, especially at night, (b) the greater tendency for calms to develop on lowlands at night in the tropics than in higher latitudes (See Law 48, under winds). It is partly for this reason that even moderately low ridges in the tropics have an appreciably different nocturnal climate from nearby plains, while there is less differentiation between ridge and plain in higher latitudes. (c) A third factor which causes greater local contrast in low than in higher latitudes is the sea breeze, which is much commoner in warm than in cool regions, and which gives to a narrow littoral strip in the tropics a climate distinctly different throughout the year from that found only a short distance inland. Sea breezes blow almost every day upon many tropical coasts because the land becomes very much warmer than the water almost every day, instead of only during hot spells in summer, as in high latitudes. Other sorts of climatic localization and their chief causes are discussed more fully elsewhere.[180]

DIURNAL AND SEASONAL DISTRIBUTION.

72. *Precipitation takes places more easily in winter than in summer and at night than by day* because precipitation occurs whenever drops, flakes or pellets are formed which are too heavy to be sustained in the air by the rising air currents. Such ascending currents are weaker in winter and at night than in summer and during the day. Precipitation reaches the surface whenever the particles are not evaporated as they fall. Much summer rain, especially above deserts, fails to reach the earth. Hence additional reasons why precipitation reaches the surface more readily in winter than in summer, and also more

[180] Visher, S. S., Local Climates in the Tropics, *Bull. Am. Meteorol. Soc.*, Vol. 3, pp. 119-121, 1922.

easily at night than by day, are because the clouds are usually lower and the lower air is more humid in the cooler than in the warmer times. Ease of precipitation does not however imply amount of precipitation, for in spite of the fact that precipitation is often induced in winter by barometric influences which would not yield precipitation in summer,[181] the total amount of precipitation received in summer is greater than that received in winter over a large share of the earth. One result of the greater ease with which precipitation takes place in winter than in summer is the fact that snow storms normally last longer than rainstorms, in spite of the fact that cyclonic storms usually move more rapidly in winter than in summer.[182] At Chicago, the average snow storm lasts 7.5 hours while the average rain storm lasts 3.9 hours.[183]

73. *Most places have a wet season and a dry season* because the distribution of precipitation throughout the year depends on (1) comparative temperature of land and sea, (2) wind direction and character, (3) intensity of insolation and hence of convection, (4) frequency of temperature changes passing the dew-point. When land is notably cooler than the sea, precipitation on the land is to be expected if the wind is off the sea. In such a wind, the air in contact with the colder land surface is cooled by radiation and conduction. Another part is cooled by being forced to rise over air piled up by the much greater friction on land than on the sea. However, the rise produced in this way is seldom sufficient in itself to cause heavy precipitation. Cyclonic and irregular winds bring more precipitation to most plains than do steady winds. Intense insolation normally produces active evaporation, strong convection currents and subsequent thunderstorms. Variations in temperature from above the saturation point to those notably below that point cause precipitation.[184]

The season during which an area normally receives the most precipitation depends upon which of the four influences enumerated above is most significant. In general the warmer regions receive most of their precipitation shortly after the date when the sun is overhead or most nearly so, because of the intensified convection. Cold regions also receive most precipitation in their warmer season because during their colder season the air can contain little moisture and hence can give up little. Furthermore, there is little moisture available for

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181 Henry and others, Weather Forecasting in the United States, *loc. cit.*

182 *Ibid.*

183 Cox and Armington, *loc. cit.*, pp. 185-191.

184 Unless such temperatures are confined to the air in contact with the surface of the land, when dew or frost formation occurs instead of precipitation.

precipitation in cold areas because winds blowing toward them have lost much of their moisture before going far inland. The shifting of the wind belts with the seasons is the dominating influence in seasonal rainfall variations for many subtropical and subequatorial areas. The winter season is the wet one on western coasts in the subtropical belt. Interior plains in mid-latitudes have more precipitation in spring and early summer than in any other four or five months.[185] Raininess in spring is a result of (1) the release of moisture accumulated on and in the ground during the winter, (2) the changeableness of the temperatures and (3) the steep temperature gradient upward. The summer rains result chiefly from increased convection and frequent reprecipitation and especially from the indraught of moisture-laden air from the sea, induced by high continental temperatures. Between the spring and the summer rains there is often a drought, frequently in June in mid-latitudes in the northern hemisphere. Winter droughts in continental interiors are due in part to the faster movement of the Lows at that season but chiefly to the fact that condensation then takes place nearer the coast than it does in summer, because of the rapid fall in temperature inland from the coast in winter.

74. *The seasonal range in rainfall varies with latitude and with relation to the ocean.* The contrast between the amounts of precipitation received in the wet season and in the dry is greater in the tropics than in middle latitudes. Indeed it seemingly varies inversely with the latitude from the edge of the doldrums to the polar regions, among places otherwise similar. The range also normally increases from the coast inland, and it probably averages less on windward than on leeward coasts. The average increase inland is largely due to the scanty winter rainfall characteristic of continental interiors. (See preceding law.) On the average windward coasts have less range than leeward coasts because the latter get a large share of their moisture from cyclonic winds which are less regular in occurrence and strength than the planetary winds. However those portions of the lee coasts which experience strong monsoons normally have well defined wet and dry seasons. Evidence showing the greater seasonal contrast in rainfall in low than in middle latitudes is given elsewhere.[186] Briefly, much more of the tropics possesses a large contrast among the monthly totals of rainfall than is the case in middle latitudes. For example, twice as large a percentage of their area receives 20% more rain in the wettest than in the driest month. In respect to greater and lesser

185 For maps of the season of rainfall see Bartholomew, *loc. cit.*

186 Visher, S. S., Variability vs. Uniformity in the Tropics, *Scientific Monthly*, Vol. 15, pp. 23-35, 1922, and The Variability of Tropical Climates, *Meteorol. Mag.*, London, Vol. 58, pp. 121-125, 154-159, 178-179, 1923.

percentage ranges also, the tropics are inferior to the higher latitudes. The great seasonal range in the low latitudes is related to the fact that most tropical localities are crossed by desiccating winds during part of the year (the Trades or land monsoons), while in other months conditions are favorable for rain, as when the doldrums pass, or when the ocean monsoon prevails, or in Mediterranean climates, when the Westerlies prevail. In higher latitudes rainfall conditions are on the average more uniform throughout the year, not only because of the general lack of drying winds, but also because there is greater uniformity in the effects of cyclonic disturbances. (See Law 80.)

75. *The frequency of precipitation tends to increase directly with the annual amount but inversely with the monthly range in precipitation* except in the monsoon areas. In other words, places with heavy rainfall are usually places of frequent rains, and wet years are years of many rainy days, on the average. However, in regions of marked seasonal distribution of rainfall, precipitation occurs fewer times in a year than in places where rainfall seasons are less marked. Since in general the seasonal range is greater in low than in high latitudes, the frequency of rain tends to be less in low latitudes than in high, wherever similar annual amounts are received. However, on windward slopes in the Trade Wind belt the frequency is high as is also the annual amount, while the monthly range is comparatively low.[187] A special illustration of the frequency of precipitation is the duration of rainfall, which increases with the latitude.[188]

76 *There are for most places two diurnal maxima and two minima for precipitation in regard to both amount and frequency. The maxima usually are at 2-5 P. M. and 3-6 A. M., and the minima at 9-12 A. M. and 11 P. M.-2 A. M. respectively.* The afternoon maximum coincides with or follows the period of most intense convection. Sometimes the afternoon maximum is delayed until early evening. The early morning maximum is caused by the marked turnover which often occurs then as a result of the excessive cooling of air above the surface layers. The forenoon minimum and the midnight minimum occur at times when heating and cooling respectively are taking place steadily but have not gone far enough to cause marked convection or overturning.[189]

There is considerable variation from place to place, and also from season to season in the precipitation yielded by the nocturnal and

[187] See Supan: Bartholomew's Physical Atlas: Meteorology, p. 19, 1899.

[188] Hann, *loc. cit.*, p. 61.

[189] For discussion of diurnal distribution of rainfall see Hann, Lehrbuch, *loc. cit.*, pp. 338-346; and Cox and Armington, *loc. cit.;* and Claxton, *loc. cit.*

afternoon maximum. In the southeastern part of the United States, and in the arid west, much more rain is received from the afternoon maximum. Indeed nocturnal rain is relatively uncommon there. In the Northeastern States, on the other hand, while the afternoon maximum predominates, it yields only a little more rain than the nocturnal maximum. A different condition prevails over a considerable area in the central part of the United States, for there more summer rainfall is received between 8 P. M. and 8 A. M. than in the other 12 hours. In the center of this area, southern Nebraska, the "nocturnal" precipitation makes up 65% of the total.[190] In the British Isles more rain falls at night than by day during the winter and the reverse is true in summer, though this condition is partly due to the corresponding seasonal difference in the length of day and night.[191] In the rainy tropics, although rain is very common from 3-6 A. M., afternoon showers are expected daily.[192]

VARIABILITY.

77. *Variability in the amount of precipitation increases with aridity,* because, (1) the chances of a constant supply of atmospheric moisture reaching an area decreases with an increase in the remoteness of that area from its source of moisture. Little moisture is carried in one continuous journey from the ocean to any moderately inaccessible point and precipitated there. Instead most moisture is precipitated and evaporated repeatedly, and sometimes it is carried away from the ocean and sometimes toward it by the winds and streams. In its journey toward the drier regions, the total supply of moisture is decreased by runoff. (2) In humid regions a considerable portion of any excess rainfall returns to the sea as runoff, whereas in arid or semi-arid regions an unusually heavy, widespread rainfall may disturb the normal moisture conditions for a considerable period. (3) The abundant soil moisture, dense vegetation, high water-table and standing water present in humid regions act as a stabilizer of atmospheric moisture conditions, whereas the relative lack of these influences in more arid regions permits greater variations in moisture conditions.[193]

78. *The amount of precipitation received by an area during corresponding intervals of time varies irregularly.* One summer or year

[190] Kincer, J. B., Day-time and Night-time Precipitation (in the U. S.) and their Economic Significance. *Mo. Weather Rev.*, Vol. 44, pp. 628-632, 1916. A summary of this paper with interpretations is given by Humphreys, *Ibid*, Vol. 49, pp. 350-351, 1921.

[191] Moore, Sir John, Meteorology, p. 262, 1910.

[192] Ward, Climate, *loc. cit.*, p. 82.

[193] Visher, S. S., Rainfall in the Great Plains in The Geography of South Dakota, *loc. cit.*, pp. 60-67.

may be wet and the next dry, or several wet years may be followed by several dry ones. Most fluctuations in precipitation in middle latitudes are related to differences in the paths, the intensity, the speed and the size of Lows, for these cyclonic disturbances cause most of the rainfall. Storm tracks are affected by anomalous variations in the temperature of continental and oceanic areas. Lows often tend to move toward abnormally warm areas. The rainfall in low latitudes, as well as in middle latitudes is closely related to the passage of low pressure areas.[194] A special feature of the irregular fluctuations in the amount of precipitation is the tendency for wet periods to perpetuate themselves, and for droughts to continue. This is perhaps never a dominating influence but undoubtedly is sometimes significant. Abundant surface waters and a high water-table certainly are more conducive to a high atmospheric humidity than are parched soil and dry lakebeds. Conversely, "All signs of rain fail in dry weather." The importance of soil and surface water in supplying moisture for precipitation is suggested by Murray's estimate that only one-fourth or one-fifth of the precipitation on the land is returned to the ocean by the rivers.[195] In some level areas the proportion of runoff is much less; for example it is only about one-twentieth for the basin of the Red River of the North. If three-fourths or more of all the precipitation on the land is evaporated locally, as seems likely, much of it probably is reprecipitated on the land. Areas remote from the ocean probably receive much more than half their precipitation in this way.

79. *Cycles of rainfall occur in many places.* Many of these are quite irregular in length and in intensity and no doubt many are due largely to the semi-periodic return, called for by the law of chance, of similar combinations of atmospheric conditions, as when analogous storms travel along similar paths. However a part of the semi-periodic fluctuation appears to be related to variations in the activity of the sun, for a correlation between sunspot periods and fluctuations in precipitation seems to be established.[196] In general continental

[194] Taylor, G., The Australian Environment especially as controlled by rainfall, 1918 (summarized by Visher in *Mo. Weather Rev.*, Vol. 47, pp. 490-494, 1919), and Visher, S. S., Australian Hurricanes and Related Tropical Cyclones, *Bull. Commonwealth Bur. of Meteorol.*, 1923; for the U. S. see Henry and others, Weather Forecasting in the U. S., *loc. cit.* and especially Henry, A. J., Secular Variation of Precipitation in the United States, *Bull. Amer. Geogr. Soc.*, Vol. 46, pp. 192-201, 1914.

[195] Quoted by Tarr-Martin, Physiography, p. 104.

[196] Brooks, C. E. P., The Secular Variation in Climate, *Geogr. Rev.*, Vol. 11, pp. 120-137, 1921; and Clements, F. E., Drought Periods and Climatic Cycles, *Ecology*, Vol. 2, pp. 181-188, 1921. See however a review and discussion of Clement's paper by Henry, A. J., *Mo. Weather Rev.*, Vol. 50, pp. 127-131, 1922.

interiors receive more rainfall when the sunspots are increasing than when they are decreasing, whereas marine climates, and some others, respond in the opposite way. The fact that different areas respond in opposite ways to changed solar activity has done much to conceal the relationship between solar changes and terrestrial weather, for wherever the rainfall of large regions are compared, the excessive rainfall received in one part may offset the deficient rainfall of another part. Another disturbing practice has been the comparison of the rainfall records of the single year when the sun's spottedness reached the maximum with the records of the single year when the spottedness was at a minimum. It is a well established fact that a single year is not so good a basis for comparison as the average of a number of years. When the rainfall data for the several years of increasing spottedness are compared with those of the years of decreasing spottedness, rather sharp contrasts become evident, which can be explained fairly well by shifts in the average storm paths, and by variations in the storms themselves.[197]

The anomalous temperature and pressures which develop from time to time over critical portions of the ocean and land are quite possibly induced indirectly by variations in solar activity. As noted in the previous law, storm paths are strongly affected by the development of such abnormal conditions. Likewise there appears to be a general shift in storm paths within the sunspot cycle. When the sun is increasing in activity, the main storm track shifts poleward,[198] with resulting changes in rainfall in a rather wide though not straight belt. The character of the change differs, however, within this belt, for at the same time that the rainfall is increasing toward the northern margin, it is decreasing at the southern.

80. *Dependability of rainfall is greater in middle than in low latitudes, and tends to increase with latitude, among places receiving similar amounts.* Most tropical cities, concerning which data are available, received three or more times as much rain in an especially wet year as in an especially dry one, while in mid-latitudes, few places receive twice as much. Indeed in fairly high latitudes in western Europe the range seldom is as great as 50%. This decrease in absolute range is the more notable because it accompanies a general decrease in total rainfall. With the smaller total annual amounts of precipitation characteristic of high latitudes, it is easier to obtain large

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[197] For a summary of evidence concerning changes in precipitation see Huntington, Earth and Sun, 1923 and Huntington and Visher, Climatic Changes, *loc. cit.*, pp. 53, 58, 59 and 93.

[198] Huntington, Earth and Sun, *loc. cit.*

percentage ranges than it is with the larger totals characteristic of low latitudes. Many illustrations of widespread and marked fluctuations in annual rainfall in tropical regions are given elsewhere.[199] A few may be mentioned here. The average rainfall at the 150 rainfall stations scattered over the Hawaiian Islands was 54.5 inches (1284 mm.) for 1918 but was 112.9 inches (2868 mm.) for 1919. Equatorial Singapore has received five times as much rainfall in one year as in another; equatorial Oceanic Island (longitude 169° E.) received 8 times as much rain in 1905 as in 1909 (19.6 inches vs. 158.9 inches; 500 mm. vs. 4040 mm.); Malden Island (latitude 4° S., longitude 155° W.), 2,000 miles (3220 km.) to the eastward, received 16 times as much in 1905 as in 1908 (3.9 in. vs. 63.4 in.; 99 mm. vs. 1610 mm.).

Not only is there a wider range in the annual rainfall in low latitudes, but excessive falls within short periods are of greater magnitude and are more frequent in tropical latitudes than in higher latitudes. (See Law 69.) On the other hand, droughts likewise are more frequent and protracted in tropical latitudes than in higher latitudes having similar average rainfalls. In parts of middle latitudes, where the normal rainfall is 40 inches (1000 mm.) or more, periods of a month without precipitation are very rare during the normal rainy season, while in the tropics even where the average rainfall is over 80 inches (2000 mm.) as in the Philippines, periods of several weeks with no rain are not very rare.[200]

The greater variation in annual rainfall in tropical latitudes than in higher latitudes appears to be related to annual contrasts in storminess. For example, some tropical localities are visited by several times as many hurricanes in one year as in another. In regions where hurricanes are almost lacking, as is the case of the equatorial stations mentioned above, there is nevertheless a sharp contrast in the annual number of disturbances produced by mild local storms or by distant hurricanes. In higher latitudes there is greater uniformity both in the number and in the severity of storms. This is partly because many of the tropical storms move poleward, where the meridians converge, and then move eastward, perhaps, nearly encircling the globe. Thus there are many more storms in high latitudes than in low. Storms are less severe in high latitudes than in low probably because they are accompanied by less condensation of water vapor. The energy

[199] Visher, S. S., Variation vs. Uniformity, *loc. cit.*, and Tropical Climates from an Ecological Viewpoint, *Ecology*, Vol. 4, pp. 1-10, Jan., 1923.

[200] Coronas, The Climate and Weather of the Philippines (Official), pp. 111-123, 1920.

liberated at condensation is the great source of the storm's energy. The cool temperatures characteristic of high latitudes permit a smaller moisture content than prevails in tropical latitudes. Hence cyclonic disturbances cause less condensation in high latitudes than in low, and therefore possess less energy.

TITLES AND ABSTRACTS OF PAPERS

Ann Arbor, 1922

Harlan H. Barrows.

Presidential Address, Geography as Human Ecology.—Printed in full, Annals, March, 1923.

M. Aurosseau.

The Geographic Study of Population Groups.

The different kinds of population groups were briefly described, and the trend of their evolution into the groups of the present day discussed. The principle was deduced that the character and development of the group are the result of interaction between the group and its origin, and it was shown that overpopulation of the region tends to be adjusted by revolutionary changes in the method of occupation. The supplanting of ruralism by urbanism at the present time, and the accompanying evolution of the region of simple and uniform production is believed to have assisted the rise of the conurbations. These in turn have made the world as a whole their area of supply, and foreshadow a period of world-overpopulation, which is an extension of the regional overpopulation of past times.

H. H. Barrows.

Memorial of Rollin D. Salisbury.

O. E. Baker.

The Agriculture of the Great Plains Regions.—Printed in full, Annals, September, 1923.

Nels A. Bengtson.

The Petroleum Industry of Ecuador.—Read by Title

William Bowie.

The Board of Surveys and Maps of the Federal Government.

The Board of Surveys and Maps of the Federal Government was created by Executive Order on December 30, 1919. This action was

based on an investigation made at a conference of representatives of the map making and map using organizations of the government called together by the President of the United States, in response to a recommendation of the Engineering Council. The Board was organized on January 10, 1920, and has continued in active operation since that time.

Prior to the creation of the Board there was little or no attempt by the various bureaus to make their work fit into that done by other organizations. This has been changed. There has been no attempt to reorganize the government mapping and surveying bureaus as this has not been considered to be a function of the Board. Standards have been adopted for the performance of various classes of work and the meeting of the representatives of the member organizations in conference at least once a month and the discussion of the surveying and mapping problems has resulted in efforts by each bureau to do its utmost to help the other organizations.

Aside from coordinating the work of the various bureaus and setting standards of accuracy for the several classes of work, the Board has studied carefully the problem of completing the topographic map of the country within a reasonable time.

The more the question of topographic mapping is studied, the more evident it is that the work should be carried on much more rapidly than at present. There is scarcely a human activity, including topographic research, that is not dependent to a certain extent on the knowledge of the configuration of the ground and geographic location of topographic features. In the interest of the commercial and industrial development of the country and for military protection, it is believed by the Board that greater activity should be shown in the completion of the topographic map of the country.

Isaiah Bowman.

The Political Geography of the Mohammedan Realm.

The Mohammedan World occupies a great area—at least three times that of the United States—extending from western Siberia southward into India and westward across Africa to the Atlantic. Bosnia represents its farthest outpost in Europe. By superimposing the line representing the limits of the Mohammedan World upon the various maps in Finch and Baker's *Geography of the World's Agriculture* and maps of mineral resources in *World Atlas of Commercial Geography, Part I, Distribution of Mineral Production,* published by the U. S. Geological Survey, it is possible to arrive at an understanding of the material strength of the Mohammedan World as its stands today. The standards

of power have completely changed since well organized mounted horsemen invaded Europe from the grasslands and deserts about the Eastern border of the Christian World. Coal and steel and the modern battleship put the Mohammedan World on a totally different plane. The main purpose of the paper was to assess the material power of the Mohammedan World and to contrast it with the main sources of power in the Christian World. If there is disunion among the score and more of nations that comprise Christian Europe, there is also serious disunion among the Mohammedans themselves. The historical manifestations of disunion and the modern tendency toward it were both reviewed and the conclusion reached that, unless Christian civilization fails altogether and disunion goes to far greater extremes, there is no cause for Europe to fear a Mohammedan invasion, though there is serious danger of repeated weakening quarrels.

Robert M. Brown.

Changing Occupations in the United States.—Read by Title.

Charles C. Colby.

The California Raisin Industry.

As the raisin industry in California developed to its present size and prosperity numerous adjustments to the natural environment were made. In making these adjustments biological and other scientific principles were utilized, a special type of economic organization was introduced, and existing social and political conditions were modified. The present analysis of this industry shows (1) that the industry is localized in the east-central part of the San Joaquin Valley because there the requisite climatic conditions for the production of raisins on a commercial basis exist; (2) that the vineyards are irregularly spaced within the producing district as the result of variations in topography, soil, water supply, and drainage, on the piedmont alluvial plain where the industry is located; (3) that years of experimentation were necessary before the situations best suited to the requirements of the several varieties of raisin grapes were known; (4) that in keeping Phylloxera and other enemies of the vine under control, drastic import and other regulations have been enforced and agricultural practices based on biological principles introduced; (5) that important statutes were written into the laws of the state to settle the conflicting claims of the ranchers during the period when the irrigation systems were constructed; these conflicting claims being in part due to the ease with which the distributaries of the several rivers were tapped for irrigation; (6) that the present prosperous condition of the

industry was attained only when a carefully coordinated system of producing and marketing the crop was established—a system adapted to the fact that the raisin producing district and the principal markets for the crop are more than 2,000 miles apart.

Nevin M. Fenneman.

The Work of the National Research Council.

The National Research Council is concerned primarily with bettering the conditions which underlie and surround research, and only secondarily with prosecuting researches on particular problems. Emphasis is laid on the fact that the Research Council is merely a *mode of cooperation* and not an institution to conduct research. Geographers are guarded against the assumption that the Research Council is directly financing investigations. Most of the money paid out for researches under the charge of the Research Council is solicited for the particular purpose in hand, largely by those who originate the project or are engaged in the investigation. The sources of these donations are here examined and classified in order to assist geographers in estimating their own opportunities. Aside from the question of financial support, the Council offers great advantages for cooperation, by supporting a central office which acts as a clearing house for information, conducts correspondence, keeps records and in general performs most of the drudgery which otherwise causes so much promising cooperative work to fail.

J. Paul Goode.

The Evil Mercator.—Read by Title.

Ellsworth Huntington.

Influenza, an Example of Statistical Geography.

One of the main objects of geography is to discover the relative effects of different physical factors in determining the location of all sorts of phenomena. It is becoming increasingly evident that in order to do this careful statistical analysis is necessary. The Committee on the Atmosphere and Man, appointed by the National Research Council, has recently made a study of influenza. Previous studies by means of the method of partial correlation coefficients has shown that various environmental factors, such as density of population, had no effect on the geographical distribution of the disease. Further studies by the same method bring out an important relationship to the conditions of the weather immediately preceding the epidemic and at the time of its maximum severity. An analysis of the results by means

of partial correlation coefficients shows that geographical factors were the main factors in determining whether the epidemic should be severe or light in different parts of the country.

W. L. G. Joerg.

The Use of Airplane Photography in City Geography.

The paper dealt mainly with that fundamental element in the study of geography, city maps on an adequate scale, say 1:15,000, which show the built-up areas, and the means now afforded by airplane photography to supply that element easily. This new means is especially valuable in the study of American cities, of which, as a rule, maps showing the built-up areas have not been available other than the topographic sheets of the U. S. Geological Survey, whose scales are too small for the "internal" study of a city, or real estate atlases, whose scales are so large that reduction and the necessary generalizations are laborious processes.

Douglas Johnson.

Some Analogous Shorelines of Partially Submerged Triassic Lowlands.—Read by Title.

The Triassic Lowlands of the Bay of Fundy region, the New Haven region, and the New York-New Jersey region have been partially submerged; the first extensively, the second slightly, and the third to an intermediate degree. Though the resulting shorelines are superficially very different in appearance, they present certain striking analogies due to similarity of physiographic history.

Wellington D. Jones.

A Classification of Climate for Use in Economic Geography.

A manuscript map was exhibited and described.

Louis C. Karpinski.—(By invitation of the Council.)

The Contribution of Mathematicians and Astronomers to Scientific Cartography.

The three fundamental problems of scientific cartography are the location of points on the earth's surface, the determination of the size and shape of the earth, and the representation on a plane surface of the observed facts. All of these problems require the services of the mathematician, the astronomer, the instrument maker as well as that of the geographer.

The ancient Babylonians contributed a fine start to scientific geography, particularly the 360 degrees in the circle and ideas connected

with the location of the position of the stars. The Greeks gave a scientific system of astronomy and of geography, culminating in the geography and the maps of Ptolemy. The Arabs made notable advance on the mathematical side, in explorations, in the recording of latitude and longitude, in perfecting and inventing instruments of observation, in the development of tables, and in cartography. The European translators in the twelfth century made the work of the Greeks and Arabs available. Scientific cartography became a matter of national concern first to the Spanish and the Portuguese and later to the Dutch, the English and the French. With the collaboration of astronomers, surveyors, mathematicians, geographers, physicists, and instrument makers, the necessary data for scientific cartography were finally made available at the beginning of the eighteenth century.

Up to the eighteenth century the two great errors of Ptolemy's maps continued on practically all the widely used maps. These two errors were in depicting the Mediterranean Sea too wide by 20 degrees and an even greater error in the width of Asia and Europe combined. The invention of the telescope, the pendulum clock, and the chronometer, made possible the corrections of these errors, through astronomical observations and by astronomical methods.

Any serious study of the development of a modern map reveals then that in part we are truly the heirs of all the ages. The maps come to us as a part of our heritage of science. The map is the achievement of countless scientists of ages past, of all nationalities seeking to record their comprehension of the universe about them. The map of the world as we have it today is a symbol of the unity of the sciences; the map is a symbol of the progress of science as the product of scholars of every land and of every age.

J. B. Kincer.

Climate of the Great Plains as a Factor in their Utilization.—Printed in full, ANNALS, June, 1923.

A. K. Lobeck.

Physiographic Divisions of Europe.—Read by Title.

The detached nature of the various similar physiographic provinces of Europe necessitates a division of features on a basis somewhat different from that used in the case of the United States where each province is a continuous unit. This detachment of related parts is due to down-dropping or inwarping of large areas or the uplifting of separate blocks so as to produce a checkerboard arrangement of highlands and lowlands.

Four main groups of features may be distinguished. First, is the Northwestern Highland belt with its associated downdropped lowlands. This area includes the highlands of Scotland, Ireland, Scandinavia, as well as those of Wales and Brittany. The associated lowlands represented by the Central Lowlands of Scotland. Other lowlands are now submerged.

The second large group consists of the Central Plains of Europe extending from southern France to Russia. This is practically a continuous belt but may readily be subdivided into several basins, lowlands, or plateau areas.

The third group includes the Massives of Central Europe with their associated lowlands. Its parts resemble the members of the Northwest highlands in physiographic character. The Spanish Meseta, the Central Upland of France, the Vosges, Black Forest, Slate Mountains, the Bohemian Massive are all examples of the Massives; the Rhine Graben and the Thuringian Basin are types of the downdropped segments.

Finally, the fourth group involves the youngest mountains of Europe with certain included lowlands and massives. This can be termed the Alpine system. It is more continuous than the older massive belts and can be traced in great swinging areas from the Pyrenees to the Caucasus and Asia Minor. The Po Basin and the Hungarian Plain are included basins; the Rhodope Mountains constitute a massive block hemmed in by the folded ranges.

K. C. McMurry.—(Introduced by Carl O. Sauer.)

The Economy of Electric Power in the Southern Appalachians.

An increase of 51 per cent in power equipment from 1909 to 1919 is a significant measure of industrial growth in North and South Carolina, Georgia, Alabama and Tennessee. The increase has been almost wholly due to added electric power equipment, in large part hydro-electric.

The several large power companies which furnish the bulk of electric power operate about 1,000,000 hydro-electric horsepower and 400,000 steam-electric horsepower. The hydro-electric plants range from installations of more than 100,000 horsepower to small plants of a few hundred horsepower. The plants are widely distributed over the area and all the large rivers are involved. The largest steam-electric plant, developing 80,000 horsepower is located at Muscle Shoals, while smaller plants are scattered throughout the system.

Hydro-electric and steam-electric plants supplement and are necessary to each other in this system. The flow of streams is irregular

and the steam plants, furnishing power during low water, lead to a more efficient and larger development of hydro-electric power than would be possible without them. Of equal importance is efficient use of power in the inter-connection of systems, by which it is possible to transmit power from end to end of the region, a distance of more than 600 miles. This makes possible a single power plant, for neither supply of power nor load fluctuates equally throughout the whole area.

The cotton manufacturing industry uses the largest amount of electric power, but nearly all industries are coming more and more to the use of this type of power. While a large amount of hydro-electric power is now developed, there is much more available, and eventually it seems likely that three to four times as much power of this type will be utilized as at present.

Curtis F. Marbut.

Soils of the Great Plains.—Printed in full, ANNALS, June, 1923.

A. E. Parkins.

The Temperature Region Map.

The paper briefly sketched the development of the idea of temperature regions and compared the temperature region maps of various authors. The map which accompanied the paper, while using the Herbertson scheme of classifying months, is original in that it is based on data of some 2,500 statements, distributed over the world. The paper discussed the distribution of the ten temperature regions and showed, by a second map, in which surface isotherms for the hottest and the coldest months were superimposed, how the migration of the isotherms give origin to the different regions The writer makes the following claims for the temperature region map:

1. It is a surface temperature map, as well as a surface temperature region map. It avoids objections geographers have to sea-level isothermal maps.

2. It shows the surface isotherms for both the hottest and the coldest months superimposed on one map. It shows the three most significant isotherms in geography. It enables one to study the speed of migration of these three isotherms. It shows temperature conditions for the hottest and coldest months and thus avoids objections geographers have to annual temperature maps.

3. It shows altitude and oceanic effects as well as any temperature map.

4. It can be used as a base map in delimiting climatic provinces.

5. It classifies the temperature conditions of the world and reveals

with great force the fact that the types of one continent are repeated in the others where the geographic factors determining temperature are similar.

6. It assists in clarifying the haziness that exists in the minds of many students regarding the temperature conditions of the tropics and the temperate and polar regions, for it shows the subdivisions of these regions in detail, yet not in such detail that the memory is burdened.

7. The map is simple and easily understood when once the basic principles are established.

William Gardner Reed.

Cotton.—Read by Title.

Cotton is grown commercially in only four or five countries, at least in such quantities that it has any appreciable effect on the world situation; cotton manufacturing is an important industry, in some eight or ten countries, and practically all the world is the consuming area for cotton goods. The result is that cotton has become a very important factor in commercial geography. Raw cotton has an important part of the export trade of the United States, Egypt, India and Peru. Cotton manufacturing is a leading industry of the United States, the United Kingdom and other European countries, and Japan. For none of these countries, except part of the United States can the supplies of cotton be obtained locally and for nearly all the raw material must be brought by sea for long distances. The regions where cotton may be grown are limited, the controls of the commercial crop being climatic and labor conditions. Cotton manufacturing apparently depends on a favorable factory development. International shipments of cotton and cotton goods, give rise to international bills of exchange in larger quantity than any other commodity, with the possible exception of grain.

G. T. Rude.

The Uses of Mean Sea Level in Determining Stability of Coast Lines.

The paper included a summary of the following topics:

The methods employed by the Coast and Geodetic Survey in determining mean sea level by a long series of tidal observations at the principal stations along the Atlantic Coast.

The distribution of the principal tidal stations along the Atlantic Coast.

The preservation of mean sea level by spirit level connections between automatic tides gauges and standard bench marks along the Coast.

Proposed plans for precise level connections between coastal bench marks and bench marks established in relatively older geological formations inland.

Carl O. Sauer.
Objectives of a Geographic Study.

M. W. Sentsius.—(Introduced by H. H. Barrows.)
Recent Views on Soil Classification.

Soil like climate is admittedly part of the human environment. But unlike Climatology the study of soils, for which the name pedology is coming into use, has not found adequate recognition in the training of geographers.

One of the first problems the pedologist has to solve to the satisfaction of the geographer is the development of an adequate soil classification. The prevailing classifications, primarily geological and physiographical in nature, for those very reasons cannot satisfy him. Recently noteworthy contributions have been made, especially by Russian and German workers toward a soil classification based largely on climate.

The newer views and principles were summarized.

H. L. Shantz.
The Natural Vegetation of the Great Plains.—Printed in full, ANNALS, June, 1923.

J. Russell Smith.
The Regional Map of North America.

The understanding of the relationship of the people to the land involves the divisions of the land into some kind of units. It also involves the consideration of the influence of many elements such as soil, surface, temperature, rainfall, humidity, location, minerals, and of many derivatives of the above such as plants, animals, industries, trade, people and their characterstics and government.

The question then arises, which shall we use as the basis of the division of our regions? The answer seems plain—no *one* in all cases, but the one or ones that really give character to a particular area. It may be surface, or climate, or location, or some other or others.

The map shown has some regions that are characterized by a crop such as spring wheat, which is in turn chiefly a climatic response. Another region is the Southern Rocky Mountains. Here the chief

characterization is surface and its resulting climates. Yet another region, the Erie Canal Belt, which includes the Hudson Valley, receives its chief characteristics as the home of man from the fact that it has unusual commercial access, a result of location, making it a great trading and manufacturing region.

Helen M. Strong.—(Introduced by J. Paul Goode.)

The Geography of Cleveland.

Cleveland is a city of contacts, a focus of natural highways. The only broad, fairly level, lowland route directly connecting the coal fields of Pennsylvania, Ohio, and West Virginia, with Lake Erie reaches the lake at this point. The mouth of the Cuyahoga is the intersecting point of three important routes, that extending east and west along the lake plain, the lowland pathway to the coal fields, and the deep water course through the Great Lakes. The valley-way is the major factor in locating, at the mouth of the Cuyahoga, the largest industrial center on the southern shore of Lake Erie.

The Cuyahoga valley is the notable topographic feature of Cleveland. It is the strategic contact for lake and land traffic, and so is crowded with steel mills, lumber yards, petroleum refineries, chemical plants, and associated industries. The industrial harbor is in the sharply meandering river, the commercial harbor is on the lake front.

Cleveland is an industrial city with important commercial activities. Three factors appear to have been chief in the development of Cleveland as a manufacturing city. (1) Cleveland is the lake terminus of the best lowland route from the Pittsburgh fields; (2) Mesabi Ore can be brought by way of the lakes at low freight cost; (3) Cleveland is located in the Northern Interior which provides a large and prosperous market for a wide variety of manufactured products.

This variety is a direct response to four influences. (1) Steel can be produced here more cheaply than elsewhere on the lakes; (2) Lake and land traffic bring a variety of raw materials to Cleveland, such as copper, wool, grain, oil and lumber; (3) Secondary industries have developed which use by-products of the primary industries; (4) The multiple demands of the prosperous markets in the Northern Interior also conduce to variety of products.

The commerce of Cleveland moves by rail and lake. Iron ore is the downbound cargo on the lake steamers, and coal the upbound cargo. Manufactured goods and merchandise chiefly are received and shipped by rail. Most of the traffic is with the East and West.

Stephen S. Visher.

Some Effects of the Tropical Cyclones of the Pacific.

A presentation of the areal and seasonal distribution of tropical cyclones in the Pacific was followed by a brief discussion of some of their obvious effects, together with inference as to their possible influence upon the distribution of life in the Pacific, upon the local diversity of climates, upon the multiplicity of tropical species, and upon certain other characteristics of animals, plants and man. The subject as to whether tropical disturbances may profoundly influence the weather of mid-latitudes by altering storm tracks and intensity, was also raised with the purpose of obtaining discussion.

O. D. Von Engeln.

The Regional Geography of Barbados, B. W. I.

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